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ELECTRON TUBES IN INDUSTRY

ELECTRON TUBES
IN INDUSTRY

BY

KEITH HENNEY

Editor, Electronics; Editor, The Radio Engineering
Handbook; Author, Principles of Radio

SECOND EDITION
TENTH IMPRESSION

PREFACE TO THE SECOND EDITION

In the preface to the first edition of this book published two years ago, it was stated that the use of thermionic and light-sensitive tubes in the communication art was well known, that many books covered that field, but that an impressive growth in noncommunication uses of tubes was then taking place. This growth has continued at an accelerating pace as industry has discovered the possibilities of the tube for process control.

It is, then, the purpose of this volume to acquaint industrial engineers, teachers, and students with the many applications of amplifiers, oscillators, phototubes, rectifiers, thyratrons, grid-glow tubes, and cathode-ray tubes to noncommunication industries. This second edition has been entirely reset. Much material taken from the more recent literature has been added; the older material has been rearranged so that it is easier to get at; more up-to-date circuits have replaced those which are now outmoded.

Care has been taken to provide the reader with rather complete reference to books and serial publications so that he may go to the source and read further on subjects which interest him. The author wishes to thank the editors of the many publications for permission to use material taken from their pages.

He wishes to acknowledge the aid of many engineers who have suggested new data and changes in the old. He is especially grateful to Dayton Ulrey, Dr. E. D. Wilson, and their coworkers at Westinghouse; W. C. White and W. R. King of General Electric; C. Stansbury of Cutler Hammer; and Donald G. Fink and Miss Kae Farrey of the editorial staff of *Electronics*.

<div align="right">KEITH HENNEY.</div>

NEW YORK, N. Y.,
December, 1936.

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ELECTRON TUBES IN INDUSTRY

CHAPTER I

FUNDAMENTALS OF ELECTRONIC-TUBE CIRCUITS

It may seem unreasonable to begin a book dealing with the rapidly growing industry based on the motion of electrons with the statement that no one knows what an electron is, but such is the case. Physicists of the highest rank who have spent years in discovering and correlating the facts of the electron's behavior do not agree among themselves as to what this elemental building block is, and they find it necessary to change their minds frequently about what they think it looks like, where it is located, how big it is, and a dozen other points of seemingly equal fundamental importance.

Fortunately the engineer need not worry about these matters; he need concern himself solely with the fact that when the electron moves, it represents energy, and that this energy can be put to work; that this work will not only make possible new processes but will lead to the simplification of old processes, effect economies, increase speeds of operation, and relieve many industrial operations of the element of human drudgery.

The radio industry, which is based on the electron tube, does an annual business of a quarter of a billion dollars; the sound-motion-picture industry accounts for an equal amount; yet in all probability not more than 1 per cent of the people engaged in these vast industries or profoundly influenced by them have any but the faintest notion of the characteristics of the electron.

Properties of the Electron.—At the outset it is sufficient to state that sometimes the electron acts as though it were a wave (whatever that may mean) and at other times as though it were an exceedingly small material particle with a mass about $\frac{1}{1800}$ that of the hydrogen atom, the lightest of all atoms. The

1

mass of the electron, when it exhibits this material-like aspect, is about 9.1×10^{-28} g.

For the sake of the reader who may be dismayed by this method of notation, which is perhaps unfamiliar to him, it must be explained that it is simply a convenient system for indicating very large or very small numbers. For example, 9.1×10^3 indicates that 9.1 is to be multiplied by 10^3, or by 1,000, which means that 9.1×10^3 is the equivalent of 9,100. On the other hand, 9.1×10^{-3} indicates that 9.1 is to be divided by 1,000, and, therefore, that 9.1×10^{-3} is equal to 0.0091. This notation is nearly always used in dealing with the excessively small distances in the atom and in the excessively large distances of the stellar universe.

All physical matter with which we are familiar is made up of 90-odd different kinds of atoms. These atoms are composed of electrons, which apparently are all alike, and another elemental "substance" made up of protons. The only difference between the atoms of one element and those of another is in the number of protons and in the number and arrangement of the electrons. No one knows exactly how these electrons are placed in the atom, but the theory that seems easiest to comprehend supposes them arranged in rings about the center, and that they are in rapid motion about this center. The center, or nucleus, as it is also called, contains all of the protons and some of the electrons as well.

The protons carry positive electrical charges while the electrons are charged negatively. It is well known that opposite charges positive and negative, attract each other, and that like charges repel each other. In the nucleus the positive protons and negative electrons are very close together—so close and bound together by such great force that it is only recently that scientists have succeeded in knocking something out of the nucleus, and then only occasionally and with great effort.

It is different with the electrons in the outer rings of the atom. These (all negatively charged) are repelling one another, and since they are at some distance from the positive protons, they are not held so tightly to the nucleus. They can be removed. It has been estimated that if 2 g. of electrons could be collected and pressed into two spheres each weighing 1 g. and these spheres held 1 cm. apart, they would repel each other with 320 million, million, million, million tons of force.

The number of units of electricity carried by each electron is known with greater accuracy than is the number of people in

New York City. This number is 1.591×10^{-19} coulomb. This is a very small quantity of electricity, so small, in fact, that 6.28 million, million, million electrons must pass a given point in an electric circuit in one second to produce a current flow of one ampere, the amount of current taken by a 100-watt incandescent lamp.[1]

Motion of Electrons.—It is the motion of electrons that interests engineers. The unit rate of the motion is the *ampere*, which is simply a measure of the number of electrons passing a given point in a second of time. An ammeter is therefore really an electron-flow-indicating machine. The ampere is a practical unit representing the rate of flow of electricity.

In a wire there are many atoms of metal making up the conductor. Some of the electrons are more or less easily detached from the atom, and under proper stimulus they will move about. As they drift, let us say toward the end of the wire, they carry negative electricity toward that point and away from the other end of the wire. Thus current is said to flow through the wire.

In their movement through a conductor the electrons bump into other electrons and into heavier atoms. Their progress is impeded, and in the bumping process some heat is generated. This opposition to the flow of current is called *resistance*, the practical unit of measurement being the *ohm*. The higher the resistance of a wire the hotter it will get under the flow of a given current. Some metals have a higher resistance than others, meaning probably that the electrons of this metal are less easily detached from their atoms, or, at any rate, that they move about less easily. Copper is generally used for conductors because it has a low resistance, is easy to work with, and is inexpensive.

Electromotive Force or Voltage.—What makes electrons move from one place to another? It is the fact that electrons carry negative charges; that a positively charged body will attract electrons, or any other negative body; and the further fact that the structure of a current-carrying element, a metal, is porous. It is like a lattice through which the free electrons can move about under the attraction of a positive charge.

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[1] On the fundamental properties of the electron see ALAN T. WATERMAN, *Elec. Eng.*, January, 1934, p. 3.

Thus, if one end of a wire is attached to a battery or source of positive charge, free electrons in that wire will move toward the positive end. It is as though some force were propelling them along the conductor. This force is called an *electromotive force* (e.m.f.) or *voltage*. The practical unit of measurement is the *volt*. It is defined as the e.m.f. that is necessary to force 1 amp. (*i.e.*, 6.28×10^{18} electrons per second) to flow through a circuit having a resistance of one ohm. The ohm, in turn, is defined as the resistance at 0°C. of a column of mercury having uniform cross section, a height of 106.3 cm., and a weight of 14.4521 g.

Law of Current Flow.—Current flows through most circuits according to a very simple rule known as Ohm's law. This rule states that the current flowing through a resistance under the given e.m.f. is inversely proportional to the resistance and directly proportional to the voltage. Thus

$$I \text{ (current)} = \frac{E \text{ (voltage)}}{R \text{ (resistance)}}.$$

If there are several resistances in series, this equation becomes

$$I = \frac{E}{R_1 + R_2 + R_3}.$$

and if this formula is transposed it becomes

$$E = I(R_1 + R_2 + R_3),$$

or

$$E = IR_1 + IR_2 + IR_3,$$

or

$$E = E_1 + E_2 + E_3,$$

which means simply that if a voltmeter is placed across each resistance, a definite voltage will be registered according to the above equation. The sum of these voltages will be equal to the voltage impressed across the entire circuit.

FIG. 1.—Simple series circuit.

In a series circuit like that of Fig. 1, the same current flows through each piece of apparatus. The voltage across each resistance depends directly upon the value of that resistance.

In a parallel circuit, however, the voltage across each piece of equipment is the same and the current through each resistance differs, depending inversely upon the resistance. The sum of the currents, however, must equal the current I flowing out of the battery. Thus

$$I = I_1 + I_2 + I_3.$$

All current flow is not governed by Ohm's law. It is one of the characteristics of conduction by metals that the resistance of the circuit is independent of the current; in other cases this independence does not exist. In certain types of conduction the current may actually decrease with an increase in voltage. Ohm's law expresses the simplest, and fortunately the most widely found, form of relation between current, voltage, and resistance.
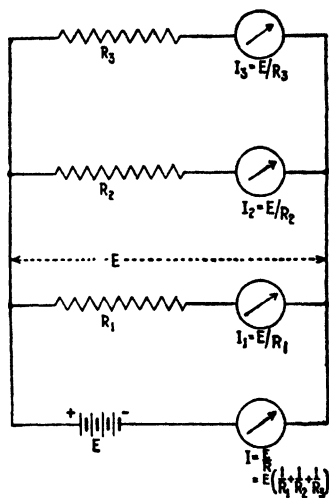
Fig. 2.—Parallel or shunt circuit.

Power in an Electrical Circuit.—The electrons in their drift from one end of a conductor to another do not have a clear path; they encounter atoms of the metal and lose some of their energy; and in this knocking about some of the energy which man applies to the terminals to force the electrons through the circuit is used up as heat. Naturally, the higher the current flow, due to a higher voltage, the greater is the number of electron collisions per second and therefore the greater must be the development of heat in the conductor.

The heat developed is found to vary as the first power of the resistance and as the square of the current. Therefore the equation of power lost in heat may be stated as

$$\text{Power } P \text{ (watts)} = I^2R = \frac{E^2}{R} = IE.$$

All electrical devices, conductors, insulators, or even producers of voltage or current have resistance. Thus a generator is not without resistance, and when it forces current through an external load, a bank of lamps for example, this current must also flow through the generator itself. Therefore there must be some heat generated within the generator and some wastage of power.

In the transfer of power from a generator to a load there is a constant conflict between the desire of the operator to get the
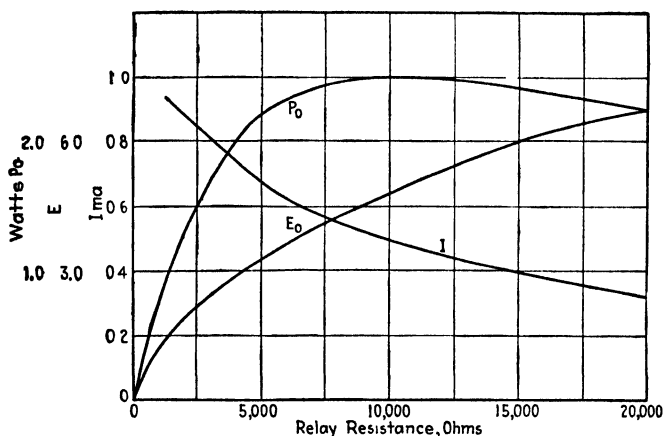
Fig. 3.—Relation between resistance of source and load (relay), power output, current and load voltage. In this case the source was a 10,000-ohm amplifier tube. Power does not fall off rapidly after the maximum.

maximum power into the load and out of the generator, and his desire to operate the system at maximum efficiency. These two desires are in practically complete conflict. If the system is operated at maximum efficiency, the maximum power output is not secured. If the conditions are adjusted for maximum power output, the generator may burn up because an equal amount of power is dissipated within the generator as appears in the load.

It can be proved by fairly simple mathematics, or by experiment, that the maximum power will be got out of a given generator and into a given load when the resistance of that load is equal to the resistance of the generator. Under these conditions half of the total power will be wasted in heating the generator

and half of it will arrive at the load, some there to be usefully employed, and some to be wasted in heating the load.

If the resistance of the load is increased, the efficiency of the system will be improved; the total power transferred will decrease, but of this total power more will get to the load than is wasted in the generator. The more the load resistance is increased, the greater the efficiency becomes, the less becomes the total amount of power involved, and of this total amount more and more will get to the load compared with the generator.

Power apparatus is usually operated at maximum efficiency rather than at maximum power transfer. Otherwise the generating apparatus would burn up. Where small amounts of power are to be transferred from the generator to the load, the condition of maximum power is usually desirable.

It is true that not much power is lost if the source and the load are not exactly matched. In fact, as Fig. 3 shows, a rather wide discrepancy may exist between load and source resistances before the mismatching effect becomes serious.

High-power Transmission.—For the transmission of large quantities of power it is standard practice to keep the current as low as possible, and the voltage as high as possible, because the power wasted in the resistance of the transmission line varies as the square of the current.

The same power can be transmitted at low current and high voltage as at low voltage and high current. Thus it is not uncommon to find transmission lines working at voltages in excess of 100,000 volts.

Such high voltages are generated at low voltage and then are stepped up by means of highly efficient transformers. Now such transformers operate on alternating current only; it is not possible to make a direct-current transformer, even though there are distinct advantages to the transmission of power at direct-current voltages in comparison with alternating-voltage transmission.

An alternator, or a.c. generator, is, in its simplest form, a conductor carrying an electric current which is mechanically rotated past the poles of a powerful magnet. As this wire or conductor goes past the magnet, a current is generated in the wire. The generator is actually much more complex than this; it has many magnetic poles, and many wire conductors.

One of the characteristics of the current generated by such a machine is that it flows first in one direction and then in the opposite direction. The reason for this strange performance may be discovered from Fig. 4. When the conductor moves up past one set of magnets, the current will flow in one direction; when the conductor moves *down* past the magnet of the other side of the alternator, the current is reversed because the direction in which the conductor moves past the magnet has reversed, *i.e.*, from up to down.

It is possible to get direct current, *i.e.*, current which does not reverse in direction periodically, from a generator by the simple expedient of using a mechanical switch which reverses the current as it enters the line taking the electrons away from the generator to their work in the load circuit. This switch is called a *commutator* and is mounted on the end of the shaft carrying the conductors in which the voltages are induced. This commutator is arranged in alternate conducting and non-conducting segments. The conducting segments are connected to the conductors which are whirled past the magnets. Carbon brushes bear on this commutator and being connected to the power lines conduct the current from the commutator to the external load.

Fig. 4.—Fundamentals of generator.

Difficulties with insulation make it impossible to generate very high voltages in such a commutated machine. In Europe fairly high voltages have been secured by connecting several machines in series, but in America it is standard practice to generate only medium amounts of direct current at voltages of the order of 220, or occasionally 500 volts for street cars; and to generate high power in a.c. machines at 10,000 to 15,000 volts.

Many believe that there are distinct advantages to the transmission of power at high voltage by direct current. At the present time, however, power is almost universally transmitted by alternating current.

Alternating-current Circuits.—In an a.c. circuit the current goes through cyclic changes starting from zero, increasing to a maximum, falling to zero, increasing to a maximum in the other

direction, and falling again to zero, thus completing one *cycle*. This is shown in Fig. 5. In a d.c. circuit the current is kept flowing in one direction only, by means of a rotating switch or commutator mounted on the generator which reverses the direction of flow into the line at the proper instant.
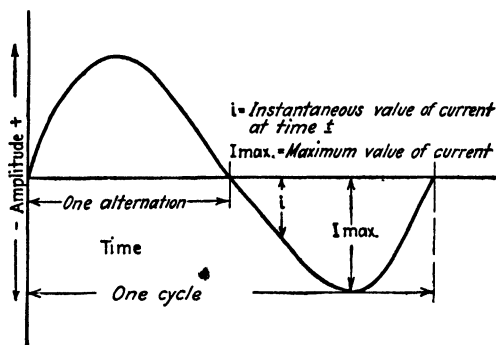
FIG. 5.—Relation between maximum and instantaneous values in an a.c. cycle.

The usual commercial circuit has a frequency of 60 cycles per second, but there are in existence circuits with frequencies of 50, 25, or other cycles.

One of the greatest promises of the electronic tube lies in solving the problem of d.c. transmission. With tubes it is not only possible to convert alternating current into direct current but also to get high-voltage direct current from alter-
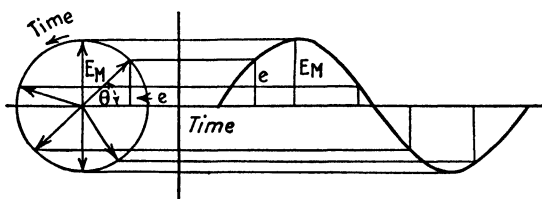
FIG. 6.—As the radius representing the maximum voltage rotates, its height above the axis changes. Plotted against time, this height traces out a sine-wave curve representing the instantaneous voltage values.

nating current. This possibility will be discussed more fully later.

Because both the current and the voltage in an a.c. circuit vary from instant to instant, it is useful to have some means of describing the magnitudes at any given instant. In the circle in Fig. 6 the length of the radius represents the maximum value

of the voltage in an a.c. circuit. This radius is constantly rotating counterclockwise, one revolution for each cycle. At any position the height above the horizontal axis of the end of the radius will represent the instantaneous value of the voltage. The exact value at any instant then may be represented by the equation

$$e = E_m \sin \theta.$$

where e = instantaneous value of the voltage.

E_m = maximum value.

θ = the angle through which the radius has moved.

The angle θ is called the *phase angle* and when the frequency of the circuit is known and the time is any number of seconds after the start of the radius from the zero point, this angle becomes equal to ωt, where $\omega = 2\pi f = 6.28$ times the frequency. Thus

$$e = E_m \sin \omega t.$$

Since the current differs throughout the cycle it is not so simple to calculate the power consumed by a circuit as in a d.c. case. It can be demonstrated that the equivalent heating effect of an a.c. current will be obtained by multiplying the maximum current by $1/\sqrt{2} = 0.707 I_{max} = I_{eff}$, or effective current.

Thus, in a resistance circuit

$$\text{Power in heat (d.c.)} = I^2 R,$$
$$\text{Power in heat (a.c.)} = I^2_{eff} R,$$

where

$$I_{eff} = I_{max} \times \frac{1}{\sqrt{2}} = 0.707 I_{max} = \frac{I_{max}}{1.41}$$

This value of I is called the effective value and the relation between maximum and effective values of voltage is the same as for current.

In all calculations of a.c. power, the effective values of current and voltage are used. In designing apparatus in which insulation is used, or in condenser circuits, the maximum voltage is used.

Apparatus Used in Alternating-current Circuits.—The current in d.c. circuits which obey Ohm's law is exactly defined by the voltage and resistance. In an a.c. circuit, however, there are

other variables. For example, the current flowing through a mile of wire stretched up on poles and the current through the same wire wound on a spool will be the same in the case of direct current but if alternating current is impressed, it will be much less in the coiled wire.

As another example consider two metallic plates separated by a nonconductor, air for example, as shown in Fig. 9. Such a device is called a condenser, and alternating current will flow through it easily if the frequency is high, but direct current cannot be forced through it.

The property of a condenser or a coil of wire by means of which the flow of alternating current is effected is called, respectively, capacity and inductance. The effect on the circuit is due to *reactance*. The condenser has *capacitive reactance* and the coil *inductive reactance;* the devices themselves are called *capacitors* and *inductors*. The actual values of these reactances depend not only upon the size of the units but upon the frequency. Thus

Fig. 7.—Inductive reactance $L\omega$ increases with frequency; capacity reactance decreases—becomes less negative. The sum of $L\omega$ and $1/c\omega$ becomes a minimum and the current a maximum at the resonant frequency, fr.

$$\text{Inductive reactance } X_L = 2\pi fL = L\omega \text{ in ohms}$$
$$\text{Capacitive reactance } X_C = \frac{1}{2\pi fC} = \frac{1}{\omega C} \text{ in ohms.}$$

It will be seen that the reactance of an inductor *increases with frequency* and the reactance of a capacitor *decreases with frequency*.

The unit of inductance is the *henry;* the unit of capacity, the *farad.* Inductances found in radio circuits vary from a few microhenries (millionths of one henry) to a few henries; in audio- or power-frequency circuits, up to many henries. The unit of capacity is the farad, but the *microfarad* (millionth of a farad) is the unit generally employed. In radio circuits the

micromicrofarad (millionth of a microfarad) is common.   These
are frequently abbreviated as follows:

Inductance:
   henry = h.
   millihenry = mh.
   microhenry = μh.

Capacity:
   farad = f.
   microfarad = μf.
   micromicrofarad = $\mu\mu$f.

The inductance of a coil is independent of current unless
the coil has an iron core, and practically independent of frequency
except at very high frequencies.

$$L = \frac{0.394\,a^2 N^2}{9a + 10b}\,\mu h$$

$$L = \frac{0.315\,a^2 N^2}{6a + 9b + 10c}\,\mu h$$

$$L = \frac{0.394\,a^2 N^2}{8a + 11c}\,\mu h$$

Dimensions in C m.
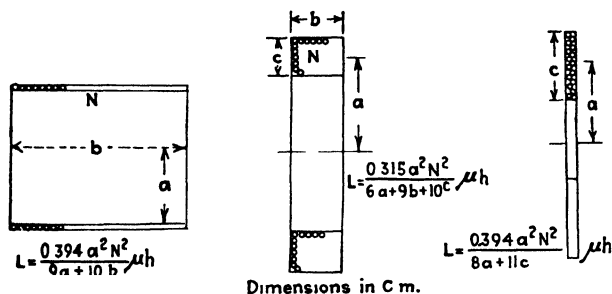
Fig. 8.—Inductance of solenoid, layer, or pancake-type inductances.

A condenser consists of two metallic plates separated and
insulated from each other.   When a battery or other source of
voltage is connected to these two plates, current rushes into the
condenser until the voltage of the condenser is equal to the
battery voltage.   If the battery is removed and a wire is touched
to the two plates, a spark will pass, indicating that the electricity
stored there has rushed out through the wire.   Now the con-
denser is discharged.

The amount of electricity that can be stored in the condenser
depends upon the voltage and upon a factor determined by the
size of the plates, their distance apart, and the nature of the
insulator separating them.   With higher voltage and larger
plates more electricity can be stored in this condenser.   The
ability of a condenser to store electricity is measured by its
capacity (or, more properly, its capacitance).   Thus,

Q (quantity in coulombs) = C (farads) $\times$ E (volts).

In condensers found in electronic circuits the insulators between the plates are mica, waxed paper, air, etc. The capacity is determined by the formula shown in Fig. 9. In this formula, *K* is the *dielectric constant* of the material used as insulator between the plates or electrodes. The kind of conductor used as the plates has no effect on the capacity. The dielectric constant of commonly used materials is given in the table below:

Material	Dielectric Constant
Air	1.0
Fiber	5.8–7.6
Glass	5 1–7.9
Hard rubber	3.0
Isolantite	6.1
Mica	5 6–6.4
Beeswax	3 2

The dielectric, or insulator, used is controlled by (1) the capacity desired, a high dielectric constant giving a condenser of high capacity in a small space, and (2) by the voltages to be used. Some insulators break down when only moderate voltages are impressed across them; others can withstand very high voltages. The ability of an insulator to stand voltage strain is called its *dielectric strength*. Some dielectrics con-

Metal plate

d ←--*Air or other insulator*

Metal plate

$$C = \frac{KA \times 885}{d \times 10^{10}} = \mu f$$

Dimensions in cm.

FIG. 9.—Fundamentals of a condenser.

sume appreciable power; others are more nearly perfect insulators in that current can pass through the condenser without much wastage of power. In a condenser the only useful characteristic is the capacity.

By a different type of capacity, known as an *electrolytic condenser*, very high capacities may be obtained, often several hundred μf, in small space.

A capacity is used as a storage reservoir of electrical energy; the energy wasted in heating the dielectric is a total loss.

Properties of Alternating-current Circuits.—The reactance of two inductances (or capacities) in series may be obtained by simply adding the individual reactances. The reactance of an inductance and a capacity in series must be obtained by sub-

tracting the capacity reactance from the inductive reactance, because they have opposite effects on an a.c. circuit. (Note: the unit of reactance, like resistance, is the *ohm*.)

The resultant of several parallel reactances is found just as the resultant of several resistances is found.
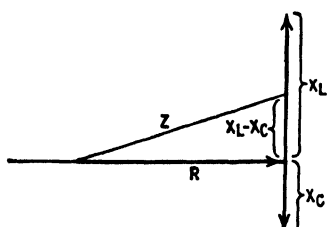
Fig. 10.—Manner in which reactances are combined.

When combinations of reactance and resistance exist in series, or in parallel, the resultant effect on the current cannot be obtained by merely adding the various items together algebraically. Reactance and resistance must be combined vectorially because their effects upon the current are different. The resultant effect of such combinations is called an *impedance,* and the process of finding the impedance of a series circuit is as follows:

1. Add the reactances algebraically, keeping in mind that a capacity has a negative reactance
2. Add the resistances.
3. Combine the resultant reactance and resistances by extracting the square root of the sum of the squares of the reactance and the resistance.

Capacity Reactance.—The a.c. current through a condenser is proportional to the voltage, frequency, or capacity. The reactance in ohms for several values of capacity and frequency is given below:

Capacity, μf	Frequency, cycles	Ohms reactance
1	60	2,654
10	60	265
1	600	265

If an a.c. voltage is impressed across a condenser, it will be found that the maximum values of current and voltage will not occur at the same instant, but that the maximum value of the voltage comes after the maximum value of the current by one-quarter cycle. If a resistance is placed in the circuit, this lag will be decreased. The time relationship between

these maximum values of current and voltage is called the
phase angle (θ) and is determined by the following relations:

$$\tan\ \theta = \frac{X}{R} = \frac{1}{\omega CR}$$

or

$$\cos\ \theta = \frac{R}{Z}.$$

Inductive Reactance.—When connected in an electrical circuit
the voltage across an inductance coil is proportional to its
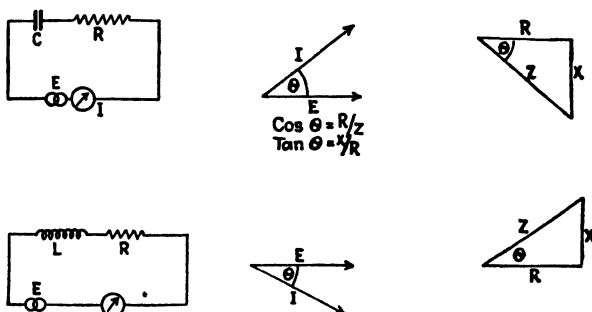
FIG. 11.—Combinations of *L*, *C*, and *R*.

inductance, the frequency, and the current passing through
it. The reactance in ohms of several values of inductance and
frequency is given in the table below.

Inductance, henries	Frequency, cycles	Ohms reactance
1	60	377
1	600	3770
10	60	3770

If an inductance is connected across an a.c. circuit, the maximum value of the current will be attained after the maximum
value of the voltage is reached. If there is resistance in the
circuit (and there always is) this time lag will be reduced. In
coils used in radio circuits the time lag is nearly one-quarter
cycle, but in iron-cored coils used at commercial power frequencies the lag is somewhat less. If this time lag is expressed
in terms of phase angle θ,

$$\cos\theta = \frac{R}{Z}, \quad \sin\theta = \frac{X}{Z}, \quad \text{or} \quad \tan\theta = \frac{X}{R}$$

A condenser placed across a circuit tends to maintain the voltage of that circuit, even though the current is decreasing. An inductance, on the other hand, tends to maintain the current flowing, even though the voltage is decreasing. In other words there is a certain amount of stored energy in both capacity and inductance, and after the source of energy is removed, or starts to decrease its supply to the inductance or capacity, this stored energy tends to maintain the voltage or current. In combination, inductance and capacity may maintain a steady flow of power (like a flywheel), even though the impressed power may vary considerably. Such is the case when a rectifier supplies spurts of unidirectional current to a filter made up of series inductance and shunt capacity. These spurts are ironed out so that an even flow of power may be taken from the filter. Thus a rectifier plus a filter will change a.c. into d.c.

FIG. 12.—When the key is pressed, the voltage e across C builds up at a rate dependent upon C and R.

Time Constants.—If a condenser charged to a voltage E is discharged through a series resistance, the voltage e, across it, will not fall to zero instantly but will decrease in an exponential curve. The voltage will fall to $E(1/\epsilon)$ or 0.368 of its original value (E) in RC sec. Similarly, the condenser will charge at this rate if it is placed across a source of voltage. It will be seen that as C or R increases, the time required to charge or discharge the condenser increases. The value RC is known as the time constant of the circuit. In a resistanceless circuit the voltage would instantly attain its final value.
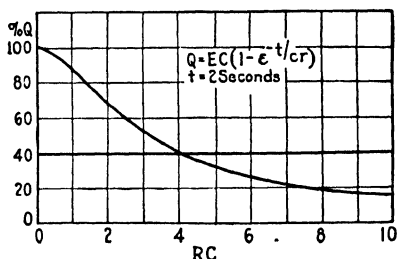
FIG. 13.—Charge having left a condenser at the end of 2 sec. for various values of RC.

In an inductive circuit the rise or fall of the *current* through the inductance is delayed by a similar phenomenon. In this case the time constant is equal to L/R showing that the greater

the inductance the longer will be the delay, the lower the resistance the longer the delay. Thus in an inductance which has very little resistance, the current can be delayed in its rise or fall by a very considerable time. In the field coils of a large generator, for example, the change of current is so slow that it can be watched on a current meter when a battery is applied to the terminals.

Considerable use is made of this phenomenon. Condensers in series with or shunted by resistances are found in many electronic control circuits. If, for example, a relay is to be closed sometime after an impulse is applied, this relay may be placed in the plate circuit of a tube, and the circuit designed to close the relay at a certain value of plate current.
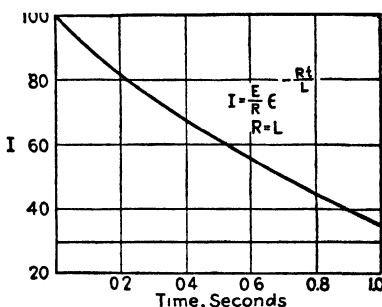
Fig. 14.—Decay of current through an inductance.

In turn, this plate current is a function of the grid voltage. In the grid circuit may be a condenser shunted by a resistance with a time constant such that when a voltage is applied, the actual grid voltage will not attain the value that will permit the relay to close until after the desired time has elapsed.

What actually happens in the capacitive case is that the charge "leaks" off through the resistance or other conductances.

If, for example a 1-microfarad condenser is shunted by a 1-megohm resistor, *RC* is equal to 1, which means that 63 per cent of the final voltage would be reached in 1 sec. Multiplying both capacity and resistance by a factor of 10 will raise the delay to a period of 100 sec.

In practical circuits, resistances of the order of 5 to 10 megohms are about the limit. If higher values are used, great care must be taken to keep down other sources of leakages such as tube sockets, wiring connections, insulation leakage, etc. Practical delays of 1 min. are about the limit, although 5-min. delays may be obtained. Longer delays may be secured better by means of electric clocks or telechron motors.

Throughout the portion of this book dealing with actual applications mention will be found of the use to which these

natural delay characteristics are put.   For example, the tendency
for an inductance to continue the flow of current after the voltage
is removed is utilized in controlled rectifier circuits to extinguish
the arc in the tube.
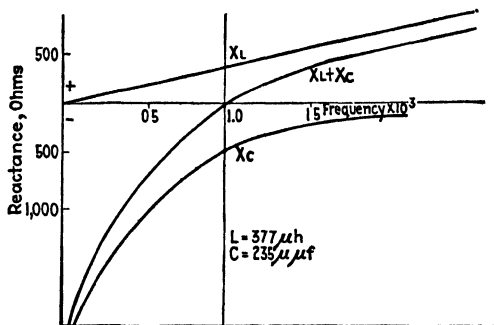
FIG. 15.—Variation of reactances and impedance $(X_L + X_C)$ near resonance.

Resonance.—Because the reactance (in ohms) of an inductor
increases with frequency and that of a condenser decreases with
frequency, the important phenomenon of *resonance* is possible
and is greatly used.   In Fig. 16 is shown the result of varying
the frequency of an applied
e.m.f. across a circuit involving
a condenser and a reactor
(inductor).   At low frequencies
the capacity reactance is high
and the current through the
circuit is low.   At high fre-
quencies the inductive react-
ance is high and the current is
low.   At intermediate frequen-
cies the current is high, and at
some value a maximum value
of current is attained.   At this
frequency the effects of the
inductive and capacitive re-

FIG. 16.—Rise of current with frequency
in a resonant circuit.

actances are equal in absolute value but of opposite effect;
therefore they balance each other, and neither has any limiting
effect on the current.   At resonance the current may be hundreds
of times the current flow at frequencies far from resonance, or
if either the capacity or inductance were short-circuited.   The

rate at which the current increases near resonance is determined by the ratio between the inductive (or capacity) reactance and the resistance. At resonance the only factor limiting the flow of current is the resistance.

Radio circuits are designed to be sharply resonant so that small changes in any one of the variables, inductance, capacity, or frequency, will produce a large change in current. The change in current with a small change in reactance or frequency is often employed for control or measurement.

Thus the capacity of a condenser in a resonant circuit may be caused to change with some varying mechanical or chemical or physical function, for example, the thickness of a rubber or moisture of a paper sheet. This sheet may be run between two plates of the condenser and the varying thickness of the continuously moving sheet will vary the dielectric constant, or the thickness of the dielectric in the condenser so that large changes in capacity, and therefore current, may be caused. These changes in current can be employed not only to register the variations in thickness (or moisture), or some other variable, but also to control the process as well.

Voltages at Resonance.—The voltage across any piece of apparatus in an a.c. circuit is proportional to the reactance and the current through it. In a series circuit containing inductance and capacity, the voltages across these units may become very high at resonance, in fact many times the voltage impressed across the circuit. This voltage is actually equal to the product of the impressed voltage and the ratio between the reactance and the resistance. This ratio $L\omega/R = 1/C\omega R$ is often called the Q of the circuit.

Thus, the voltages in a series circuit are:

$$E_R = IR,$$
$$E_L = IL\omega = \text{impressed } E \times Q = \frac{EL\omega}{R},$$
$$E_C = \frac{I}{C\omega} = \text{impressed } E \times Q = \frac{E}{C\omega R}.$$

If, for example, a circuit is made up of 0.25 henry and 0.001μf which collectively may have a resistance of 1,000 ohms, and the frequency is varied from 8,000 cycles to 12,000 cycles, the

voltages at resonance (10,100 cycles) will become 157 if the impressed voltage is 10.

Power in an Alternating-current Circuit.—In an imaginary electrical device having pure capacity or inductance (no resistance) no power is wasted in heat. Energy flowing into an inductance maintains an electromagnetic field about the coil and energy flowing into a condenser maintains an electrostatic field in the dielectric of the condenser. Numerically this energy is

$$\text{Energy in inductance} = \tfrac{1}{2}LI^2.$$
$$\text{Energy in capacity} = \tfrac{1}{2}CE^2.$$

Because the current and voltage do not reach their maximum values at the same time in a circuit containing reactance, the
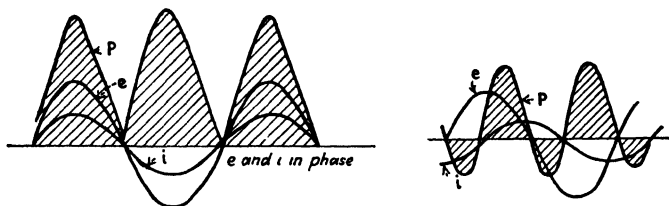
Fig. 17.—Power as the product of voltage and current in resistive and inductive circuit.

power is not so simply calculated as in a purely resistive circuit. The effect of inductance at certain portions of the cycle may be seen in Fig. 17. The product of voltage and current in these portions gives negative values of power. At these periods energy stored in the magnetic field of the inductance is given back to the line.

Instantaneous power is the product of the instantaneous values of current and voltage; average power, or the power supplied over a period of several cycles or longer, depends upon the phase angle as well as upon the voltage and current. Thus

$$\text{Instantaneous power} = ei.$$
$$\text{Average power} = E_{\text{eff}}I_{\text{eff}} \cos \theta,$$

where

$$\theta = \tan^{-1}\frac{X}{R}.$$

The factor cos θ is called the *power factor*. In some radio circuits it may be as small as 0.005, thus indicating that a very

, small amount of power is wasted in the resistance of that circuit; most of the energy is used to maintain the field. In power circuits of commercial frequencies the power factor is of the order of 0.7 to 0.95.

Application of Electron Tubes to Industry.—Many optimistic statements have been made regarding the adaptation of electron tubes and circuits to various industrial control functions. Unfortunately the spread of tubes throughout industry has been slow; and there are several obvious reasons. The depression made it impossible or unwise to spend capital funds even for changing processes which might increase production or lower cost and thereby better the competitive position of the user. Electron tubes, in the minds of the uninitiated, are fragile and have a short life. The education of the plant superintendent and engineer has been slow and not always marked by a knowledge of what the industrial man wants. The promulgators of electronic equipment have been engineers familiar primarily with this equipment and unfamiliar with the problems the tubes were supposed to solve.

It seems evident that electron tubes must go into industry to perform new services; or to improve old services either by making them more economical or faster, which amounts to the same thing. So far the economy element has not been of great importance; usually the electronic control equipment is more expensive than existing equipment, and even if the new apparatus performs better than the old, economy either in first cost or in maintenance has been of profound importance during the period that electronic equipment has been available.

What the Electron Tube Can Do.—In the following pages there will be found described several types of electron tubes, and many applications that have already been made. In general these tubes may be divided into two broad groups, the thermionic tube and the light-sensitive tube. Both may be divided into vacuum and gaseous, or vapor, types. The thermionic tube gets its impulse from an electrical voltage fundamentally, but this voltage may arise in many ways, as by a temperature change, a phase difference, current flowing through a resistance, by inductance, by a mechanical movement, etc. The light-sensitive tube, as its name implies, gets its impulse from a beam of light—a totally new concept of the importance of light.

The vacuum thermionic tube produces a changing current in response to a changing voltage. This changing current may be an exact replica of the changing voltage, and if permitted to flow through a load, the voltage change across this load may be many times greater than the changing voltage which provided the original impulse. In other words, the vacuum thermionic tube (except the diode) is fundamentally an amplifier.

The gaseous thermionic tube is fundamentally a rectifier. Its output current change bears no relation to the varying voltage impulse except that it is permitted to flow when the proper voltage impulse is provided. It is a much more efficient tube than the vacuum tube in that the power lost within itself is small compared with the power delivered to a load. It may handle thousands of kilowatts of electrical energy at very high efficiency and have a long life.

The light-sensitive tube converts a beam of light energy into some form of electrical energy, either a voltage or a current. This electrical energy may be amplified or used directly to perform whatever the engineer desires.

It should be pointed out that amplifier tubes or phototubes act as rectifiers when operated with alternating current on their anodes. They will only conduct current when the anode is positive with respect to the cathode, and when operated on alternating current they may perform their desired function of amplification or control or light-to-electricity conversion just as when operated on direct current. At the same time, however, they will be performing the function of rectification.

Disregarding the economic angle it is worth while considering what the electron tube can do. As a relay[1] the electron tube has the advantage of the magnetic relay in that it is faster and requires less power to operate it. If the power available is of the order of 1 watt or greater and if the relay need not operate in less than $\frac{1}{20}$ sec., the magnetic relay is satisfactory. At higher speeds and with less impulse power, the amplifying ability of the electron tube gives it a tremendous advantage over the older form of relay. Electron-tube apparatus may break a circuit in a fraction of a cycle; several cycles are required by older equipment.

[1] STANSBURY, C., Factors Affecting Adoption of Electronic Control in Industry, *Elec. World*, Jan. 27, 1934.

In controlling power apparatus, motors, etc., it seems that existing equipment cannot appreciate the advantages of the tube. That is, existing equipment has such a design and application that little improvement can be effected by controlling it by an electron tube. The future may see this situation change appreciably, as the advantages of new equipment designed around the abilities of the tube become better known.

In a great many cases, admittedly special and not general, tubes can now prove their value, for example, in the machine tool field where a lathe has its speed varied by the operator by rather complicated mechanical devices. In the illumination field the tube provides a simple and versatile control, particularly where the control function is to be exercised at a distance from the source of illumination.

The tube can be used, often to advantage, in any case where a variation of an electrical or physical or chemical quantity occurs, for example, voltage, current, resistance, frequency, etc., or to temperature, moisture, position in space, weight, etc., and to chemical changes such as opacity, color, turbidity, acidity, conductivity, etc. The electron tube acting alone or in combination is a useful tool; time alone will tell how important it becomes in industry.

At the present time the most promising tube applications are those where the operation or control cannot be exercised in any other way. Here, of course, the economic problem is not severe, since the tube has no competitor. It is a fact, however, that when a tube performs a function that cannot be handled in any other way, invention will strive to find the other way, if it is cheaper, and therefore tube applications must continually struggle against high cost. As tubes go into service more generally, costs will go down.

Tubes are important where they reduce time or cost or increase safety. In research or laboratory uses, cost is not so important as the manner in which the tube produces results.

Metal tubes will probably go a long way toward getting around the average factory man's inhibitions against tube apparatus.

CHAPTER II

THERMIONIC TUBES

Considerable mystery surrounds the electron tube in the lay mind and in that of the electrical engineer not directly experienced in tube problems or circuits. This mystery has probably arisen from the unreality of radio; of getting signals from an ether which does not exist.

The terms used by an engineer accustomed to thermionic or photoelectric tubes are stranger to the power engineer, than are the latter's terminology and values of currents, powers, etc., to the electron-tube man.

Much of this mystery can be dispelled by considering the tube not as a thyratron, or grid-glow tube, but by the primary functions which the tube can perform. Thus, a tube will act as a nonmechanical contactor, opening or closing a circuit; it will transform light energy into electrical energy; it will amplify power or voltage or current or generate alternating current from a battery, etc. Not all tubes can perform all functions, but some of them can perform several functions, often simultaneously. In combination, a phototube and a grid-controlled rectifier can control a 5-hp. motor from the energy existing in the beam of light from a pocket flashlight. With the addition of one or more amplifier tubes the light from a star so distant that it takes millions of years to reach the earth can be used to shut down or start up this same motor.

Tubes are spoken of in literature not only by their structure, as a *triode*, which is a three-element tube, but by their function in the particular circuit under discussion, such as a *rectifier*, *oscillator*, or *amplifier*. In each of these latter cases the tube might be a triode, perhaps the same triode in all cases, or it might be a different type of tube in each case. In many cases trade names have further confused this picture. It seems best to call the tube by its function in the circuit wherever possible, *i.e.*, rectifier, relay tube, amplifier, etc., but often

<p align="center">Electron Tubes</p>

Type of tube	Vacuum or gas	Power	Impulse	Name

<p align="center">Function: Switch, Contactors, Variable Resistors</p>

Type of tube	Vacuum or gas	Power	Impulse	Name
Light-sensitive	Either	Microwatts	Light	Photocell, phototube
3 or more elements.	Vacuum	Watts	Manual or automatic	Amplifier, Pliotron (G.E.)
2 elements	Gas (neon)	Watts	Condenser discharge	Neon or glow tube
3 or 4 elements.	Gas	Kilowatts	Manual or automatic	Grid-controlled rectifier Thyratron (G.E.), Grid-glow (W.E. & M.) Igniter tubes

<p align="center">Function: Amplification of Current and/or Voltage or Power</p>

Type of tube	Vacuum or gas	Power	Impulse	Name
3 or more elements.	Vacuum	Watts	D.c. or a.c.	Amplifier, Pliotron (G.E.)

<p align="center">Function: Rectification, Conversion of Alternating Current to Direct Current</p>

Type of tube	Vacuum or gas	Power	Impulse	Name
2 elements.....	Gas	Watts at low voltage	A.c.	Tungar (G.E.) Rectigon (W.E. & M.)
2 elements..	Vacuum	Kw. at high voltage	A.c.	Rectifier, Kenotron (G.E.)
2 elements .	Gas	Kw. at high current	A.c.	Rectifier, Phanotron (G.E.)
3 or 4 elements	Gas	Kw. at high current	A.c.	Controlled rectifier Grid-glow (W.E. & M.) Thyratron (G.E.) Igniter tubes

<p align="center">Function: Generation or Inversion; Conversion of Direct Current to Alternating Current</p>

Type of tube	Vacuum or gas	Power	Impulse	Name
3 elements.....	Gas	Kw. at high current	D.c.	Grid-glow, Thyratron
3 elements.....	Vacuum	Kw. at high voltage	D.c.	Oscillator, Pliotron

Transformation—one voltage to another, one frequency to another, all of above tubes used singly or in combination.

more than one function takes place at once. Then the author and the reader must pick their way carefully over an occasional bit of rough going.

The table on page 25 is an attempt to classify the functions performed by electron tubes and to indicate the meaning of some of the names applied to them.

Electron Tubes.[1]—The most direct application of the flow of electrons is in the electron tube. A source of electrons, the *cathode*, emits these carriers of electricity which are collected by an *anode*. The elements, cathode and anode, are usually enclosed in a glass envelope which is highly evacuated. In some cases gas of a known element and to a known pressure is admitted after this pumping process.

Types of Tubes.—The electrons come from a cathode, which may be (1) heated (thermionic), (2) illuminated (photo-electric), (3) mercury pool (mercury-arc rectifier), or (4) cold (cold-cathode tube, Raytheon rectifier, etc.).

Tubes may be classified according to the number of electrodes, a two-element tube being called a *diode*, a *triode* being a three-element tube, and so on, to *tetrodes* and *pentodes*.

Tubes may also be divided into groups according to whether they are high vacuum, whether they have *gas* or an element which vaporizes in the bulb.   '

No matter what the nature of the tube, the electrons which perform such multitudinous and important functions must in some manner acquire a supply of energy in addition to what they ordinarily possess. This new energy is to permit them to escape from their prisons out into a void through which they can fly to another prison there to deliver their supply of electricity. In the case of the thermionic tube, as its name implies, this energy comes from heat. The wire composing the filament of the tube is heated until the electrons are so speeded up that their energy is sufficient to break through the forces ordinarily binding them to the wire. In the case of the phototube, the source of energy is a beam of light, feeble as that may seem to be.

These electrons after leaving the filament, or photosensitive surface, speed with extremely high velocities toward another

[1] An excellent series of articles on "Electronics and Electron Tubes" appeared in the *Gen. Elec. Rev.* by E. D. McArthur, March to December, **1933.**

element within the glass envelope.   The velocity with which the electrons arrive (high vacuum only) may be computed from

$$v = 5.95 \times 10^7 \sqrt{V},$$

where v is the velocity in centimeters per second, and V is the voltage between the source of electrons and the element toward which they are speeding.   So great are these velocities that it is more convenient to speak of electron velocities in terms of the voltage through which they fall.   Thus a velocity of 100 electron volts means an actual velocity of approximately 11,600 miles per second.

The Thermionic Vacuum Tube.—Consider an electrode, say a filament of tungsten wire which can be heated from a battery

F = Filament   P = Plate or Anode   Sg = Screen Grid
G = Grid (control)   C = Cathode   Sup G = Suppression Grid
                                               H = Heater Filament
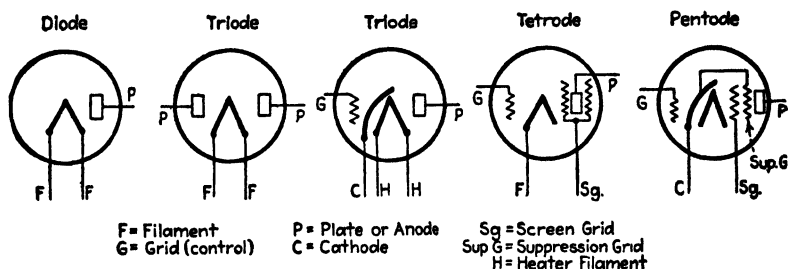
Fig. 1.—Classification of tubes by number of *essential* elements.   The heater filament serves no circuit function; it merely causes the cathode to emit.

(usually called the "A" battery) or from a transformer connected to a power supply.   Atoms and electrons in this wire are in a constant haphazard motion with a velocity which increases with temperature.   If the wire (called the cathode) is heated to a sufficiently high temperature, some of the electrons will have enough energy to escape from the surface, much as water molecules escape from the surface of water in a vessel. The temperature required before electrons are emitted depends mostly upon the nature of the cathode surface.   At a temperature of 2400°K. a pure tungsten cathode will emit about 0.12 amp. per square centimeter of surface.

If the surface is properly coated with the oxides of some elements such as barium, calcium, etc., or if thorium oxide is applied to the tungsten filament, the emission will be greatly increased, with the result that lower temperatures can be used with increased filament life.

The relation between emission and temperature[1] is complicated, but small increases in temperature will cause large increases in emission. A filament operating at a dull-red heat will have its emission doubled if the temperature is increased by only 100° and a 1 per cent change in the current through the filament may cause a 20 per cent change in emission of electrons.

One formula for emission given by Dushman is

$$I = AT^2\epsilon^{-\frac{b}{T}},$$

where I = emission current in amperes per square centimeter of emitting surface.

T = degrees Kelvin or absolute temperature.

b and A = constants depending upon the cathode material.

ϵ = natural base of logarithms.

It is seen that the smaller the factor b in the above equation the greater will be the emission. The table below[2] shows that for a given emission a thorium filament can be operated at a lower temperature than one of pure tungsten.

Cathode material	A	b	Amp. per sq. cm.	°K	Amp. watt	°K
Tungsten..................	60.2	52,400	0.12	2,400	0.004*	2,500
Thoriated tungsten.	3.0	30,500	0.80	1,900	0.075	2,000
Oxide-coated..............	2.88	19,500	0.20	1,100	0.050	850

* Amperes emission per watt expended in heating the cathode. See STILES, W. S., Thermionic Emission, *Radio Research, Special Report* 11, H. M. Stationery Office, London, 1932. The values of temperature given here apply to the immediately preceding data.

In the amplifier tube used in radio receivers the currents carried by the electron stream coming from the filament may be of the order of milliamperes; in tubes used to level elevators the current will be not much over 0.1 amp.; in the largest amplifiers used in transmitting stations (speech and music) the maximum current per tube may be only 6 amp.

Small as these currents may seem to a power engineer, it must be remembered that they involve the mass motion of many

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[1] RICHARDSON, O. W., "Emission of Electrons from Hot Bodies," Longmans, Green & Co., 1921; On electron emission see also DUSHMAN, SAUL, *Elec. Eng.*, July, 1934, p. 1054.

[2] "International Critical Tables," vol. 6, p. 53.

billions of electrons all under perfect control and all seemingly speeding on their task of converting energy of one form into another, silently, efficiently, with no moving parts and with a tube life that in carefully operated apparatus may run 4,000 hours or more.   These small currents at voltages of 10,000 or more volts may represent considerable power.   The thermionic tubes met with in radio receivers are nearly always high vacuum tubes; *i.e.,* they have been highly pumped and then sealed off with great care taken to see that no gas gets into the glass envelope during the life of the tube.   In industry, some tubes are high vacuum, others contain gas or vapor at various pressures admitted after
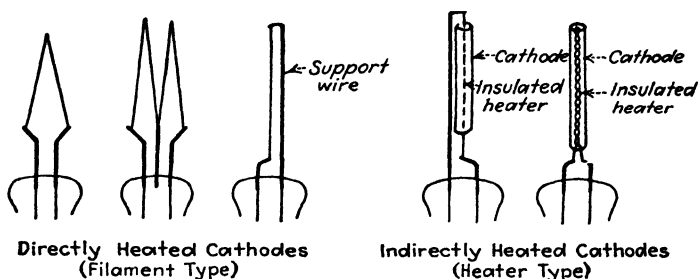

Directly Heated Cathodes   Indirectly Heated Cathodes
(Filament Type)   (Heater Type)

Fig. 2.—Types of cathode.

the tube has been pumped free of undesired gas.   The pressure in an amplifier tube (high vacuum) is of the order of 10^{-8} atm.[1] A small quantity of water vapor will ruin a tube.   Other gases may, in time, be released from the metallic elements within the tube structure.   Often the elements may run at red heat making it easy for gas molecules to escape and spoil the emission characteristic.

In gaseous tubes the currents may run into amperes or even thousands of amperes, compared to milliamperes or a few amperes in high-vacuum tubes.   The pressure in gaseous tubes runs from 10^{-6} to 10^{-3} atm.

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[1] There are several methods of rating vacua—thus, one standard atmosphere is a pressure of 760 mm. of mercury; a micron is a pressure of 0.001 mm. of mercury; a bar is one dyne per square centimeter.   One bar is the equivalent of 0.00075 mm. of mercury or 0.0133×10^{-6} atm.   One micron equals 1.333 bars.   A high-vacuum tube is one in which the pressure has been reduced to about one bar (or one micron).   Even at this pressure there are about 2.56×10^{13} molecules of gas per cubic centimeter.

In general there are two types of thermionic cathode, the true filament in the shape of a V or W, or of a hairpin, and the "indirectly heated" cathode. In the latter case a heated filament which does not emit electrons to any extent is surrounded by a coated sleeve which constitutes the true cathode or source of electrons. This sleeve is heated by the filament inside it (called the *heater*) but is electrically insulated from it. The latter type of tube makes it possible electrically to separate the heater circuits from the emitting surfaces. In general, they require considerably longer time to arrive at an operating emission temperature compared with filament-type tubes.
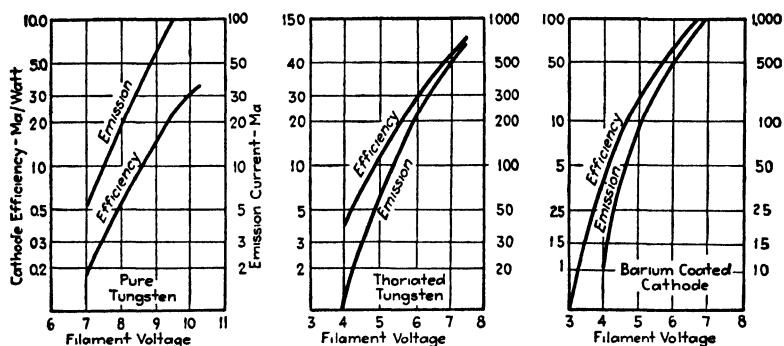

Fig. 3.—Efficiency and emission of various emitting cathodes.

These electrons, emitted from the coated filament or sleeve, congregate in the space near the cathode and collectively make up a cloud called the *space charge*. Since these electrons are negatively charged, they will tend to repel other electrons leaving the cathode, and soon equilibrium will be established between the pressure of oncoming electrons and the pressure exerted by the electrons already escaped from the cathode.

Suppose now another metallic plate is sealed into the tube and is made positive (by a battery usually called the "B" battery) with respect to cathode. A number of electrons will reach the *plate* and give up their charges there. This amounts to a transportation of electricity from cathode to plate and an ammeter in the plate circuit will show a flow of current.

Edison, Fleming, and DeForest.—The fact that an electron current could be established through a vacuum in the manner described above is known as the *Edison effect* after the discoverer

of the phenomenon. Fleming, in England, in 1897 made the first practical use of the phenomenon. He made a wireless signal detector using the Edison effect. Much later, (1906) DeForest in the United States made a further remarkable and vastly important discovery, the value of placing a *grid* of wires between the cathode and plate, thus forming the three-element tube (triode) and making possible the radio, long-distance telephone, sound pictures, and now the electronic industry.

The Two-element Tube.—Consider again the diode, *i.e.,* a tube having a heated cathode or source of electrons and a plate or collector of electrons called the *anode*. So long as this plate is positive with respect to the cathode even if it gets hot enough to emit electrons, electrons will be attracted to it thereby setting up a current in the anode circuit. If, on the other hand, the plate is negative with respect to the cathode, no electrons will go to it and in fact will be repelled from it. Thus, if an alternating voltage is placed between cathode and plate, current will flow only during the half-cycles during which the plate is positive. Therefore, the two-element tube will act as a rectifier, *i.e.,* it will convert alternating current into direct current. In its plate circuit will be a pulsating current passing whenever the plate is positive.

These pulses of current, always flowing in the same direction can be used to charge a battery or serve any other purpose where such pulsating direct current can be utilized. These pulses may be supplied to a condenser-inductance system, which in turn will release a steady flow of current having practically the same characteristics as direct current generated by a chemical battery or by a rotating dynamo.

Now the electrons in such a tube have enormous distances to go before they arrive at the plate with their burden of electricity. It has been estimated that the ratio between the dimensions of an electron and the distance from cathode to plate is about the same as the diameter of a baseball and the distance from the earth to the moon.

In the transfer of electricity from cathode to anode some power is lost. If the power put into the tube is measured by the product of voltage and current, and if this power is divided by the square of the current, a value of the internal resistance of the tube will be obtained. This resistance is analogous in

every respect to the internal resistance of a generator. Current flowing through this resistance produces heat and represents power that is wasted. Since the useful function performed by a tube is to supply power to some *external* circuit, this internal power loss is a definite waste—and unfortunately in high-vacuum tubes represents a fairly high percentage of the total power supplied to the tube. In other words, the efficiency of the high-vacuum tube is not very high.

The current carried by the electrons, flowing through this fictitious internal resistance, represents a voltage drop which is more or less proportional to the current flowing. In a gaseous tube this voltage drop is independent of the current; and it is a much smaller proportion of the plate battery voltage supplied to the tube, than in a high-vacuum tube. The latter tube is used where complete control of the anode current is required.
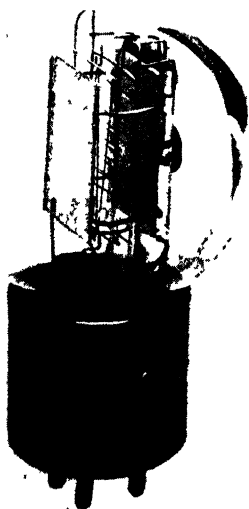

Fig. 4.—Tube widely used in telephone amplifiers.

Saturation Effect, the Space Charge.—The current through the tube is limited by two factors: the supply of electrons and the behavior of these carriers after they leave the cathode. The supply of electrons is limited. At any given temperature there is an upper limit to the number that will escape from the filament or cathode. To get all of these electrons, or a major part of them, to the plate or anode, requires a certain minimum plate voltage. A higher plate voltage will not appreciably increase the plate current because there are no more electrons. This is known as the saturation effect. The plate is getting all of the available electrons.

Suppose this saturation value of plate voltage is fixed but the temperature of the cathode is raised. Now there is a new

supply of electrons and, of course, more plate current will flow. This effect is shown in Fig. 5.

If, however, the plate voltage is low increasing the cathode temperature will result in greater plate current only up to a certain point, and then further temperature increase will not increase the plate current.

This effect is caused by the following phenomenon: Some of the electrons do not reach the plate because the velocity with which they leave the cathode is not sufficient to carry them into the field of the plate through the space charge of mutually repellent

Fig. 5.—Limitation of current by low temperature or by space charge.

electrons. Therefore increasing the numbers of electrons increases the current to the plate very slightly. To get greater
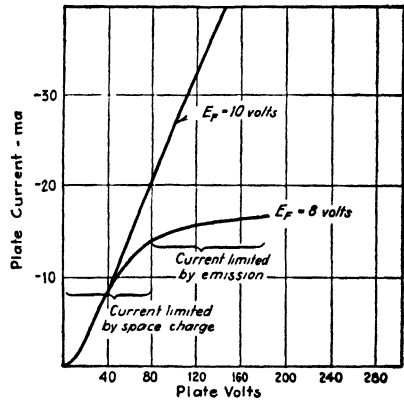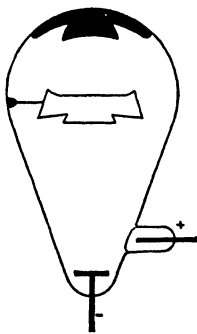

Fig. 6.—Early form of cathode-ray tube. Electrons emitted by the negative terminal, drawn onward by the positive potential, strike the end of the tube unless obstructed.

plate current some means must be provided for neutralizing this negative space charge. This can be accomplished (1) by increasing the plate voltage (2) by putting gas in the tube, or (3) by introducing another element (grid) into the tube.

Control of Electron Stream.—The flow of electrons from cathode to a positive plate may be controlled by electromagnetic or by electrostatic means. The discovery of this fact led, by a series of remarkable researches, to the present-day theories of the constitution of matter.

One of the earliest electron tubes was a simple glass cylinder with electrodes sealed into the two ends. When the tube was pumped to the proper degree of vacuum, and sufficiently high voltages were impressed upon the electrodes very peculiar, and often very beautiful, visible effects were obtained. At still lower pressures the visible effects

disappeared and instead the walls of the cylinder began to glow (fluoresce). A most important discovery was the fact that an object placed in the path of the rays cast a shadow on the side away from the negative terminal. Therefore, it was reasoned, the rays consisted of particles proceeding from the negative terminal toward the positive terminal.

Then it was discovered that a magnet held near the tube deflected the beam of particles; and then it was found that plates charged electrostatically also deflected the beam. These deflections were in such directions as to confirm the feeling that the particles were charged with negative electricity.

These particles were actually electrons; and a cathode-ray tube is a tube in which electrons projected from the negative
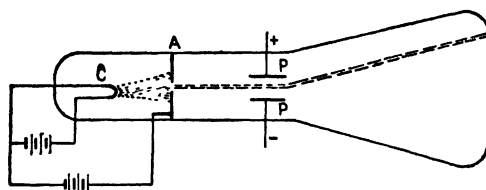

Fig. 7.—Deflection of election beam by electrostatic plates.

cathode proceed toward a positively charged terminal. The cathode rays were simply beams of electrons. Another discovery, also leading to an electron tube, was the fact that if these electrons struck a target with sufficient speed, an invisible ultra-short wave-length radiation was secured. This radiation has all the qualities of ordinary visible light plus the fact that it is exceedingly penetrative. This radiation was called x-rays, a name that has continued to the present day.

By measuring the extent of the deflection of the electron beam with given voltages and currents in the electrostatic or electromagnetic systems, J. J. Thomson was able to calculate the ratio of the charge of the negative particles to their mass. Later, Millikan and others measured the quantity of electricity carried by each electron and then the mass could be computed. It was found that the mass was extremely small, and it is now assumed that the charge carried by a single electron is the unit quantity of electricity.

Electromagnetic Control of Electron Beam.—Electrons leaving the cathode and proceeding toward the positive plate may be

accelerated or retarded by placing the tube in a coil of wire and passing sufficient current through this wire to create a field in which the electrons are given a path that is curved. If sufficient curvature is imparted to the electron path, the electrons will never reach the plate and no current will flow to it. Such a tube is variously called a magnetron[1] or a magnetostatic tube. The terminology here is not well defined at present. Of course, the magnetic field may be constant, and plate-current control may be by electrostatic means, or the variations in plate current may be produced by a varying magnetic field.

Present-day models of the cathode-ray tube are in everyday use in laboratories and in some commercial applications. Their characteristics are described later. Here, too, the electron beam may be controlled by either electrostatic or electromagnetic means.

Electrostatic Control.—It is possible to control the current flowing in a two-element tube by wrapping a metallic screen about it and putting sufficient

Fig. 8.—Tube in which electrons are controlled by an electromagnetic field.

negative voltage on this screen to retard the electrons. A curve showing such control will be found in Fig. 9.[2]

In general, however, the electrostatic control is exercised by putting within the tube a third element, the grid, an invention of the greatest importance.

The curve in Fig. 10 shows the effect of placing a two-element high-vacuum rectifier in an electromagnetic field. In this case the tube was an FP-85 and was placed in a solenoid about 4 in.
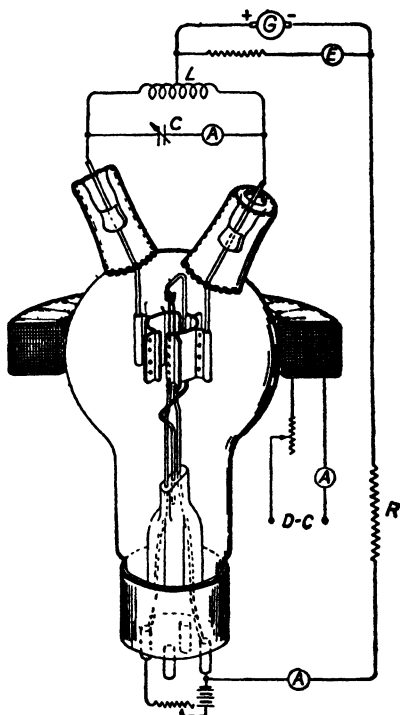
[1] HULL, A. W., *The Magnetron*, Am. Inst. Elec. Eng., September, 1921.
[2] CRAIG, PALMER H., The Kathetron, *Electronics*, March, 1933, p. 70.

inside diameter, and of 6 in. length consisting of 400 turns of wire capable of carrying 5 amp.[1] The tube dimensions and other variables are related (for complete cut-off) as follows:

$$H \text{ (gauss)} = \frac{6.72\sqrt{E_p}}{r}$$
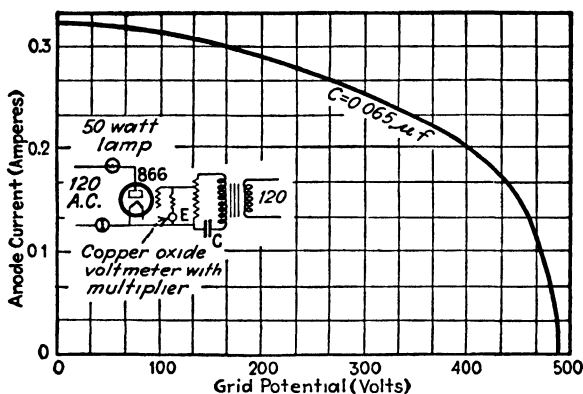
where r = anode radius in centimeters.

Fig. 9.—Control of current in two-element gaseous rectifier by means of an external electrostatic shield.

The Three-element Tube.—When the third element of DeForest was added to the diode, the complexity and usefulness of the thermionic tube were enormously increased. This third element is usually an open grid of wire situated between the cathode and the plate. Its potential with respect to the cathode may be made negative or positive (by a battery, called the "C" battery) having the effect of retarding or accelerating the rate at which electrons released
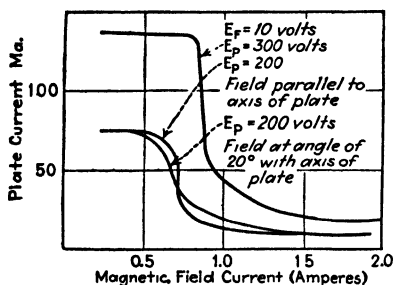
Fig. 10.—Control of current in two-element rectifier by electromagnetic field.

from the cathode arrive at the plate. In being able to increase or decrease the space charge, the grid becomes a modulating electrode and within certain limits every change

[1] McArthur, E. D., *Gen. Elec. Rev.*, June, 1933, p. 288.

in voltage applied to the grid will cause a corresponding change in the plate current. Thus if the plate current is, say, 10 ma., with any steady voltage on the grid, and then if this grid voltage is changed plus or minus this steady value at a steady rate, say at 60 cycles per second, the plate current of 10 ma. will rise and fall with a 60-cycle frequency. This plate current is a direct current pulsating at a 60-cycle rate. By proper means these pulsations can be caused to operate a 60-cycle voltmeter or run a synchronous clock or motor or perform any other work in a device designed to run from this a.c. frequency.

The Amplification of a Tube.—Because the grid is much nearer the cathode than is the plate, variations in grid voltage are more effective than the plate voltage in changing the plate current. The ratio between the two effects is known as the *amplification factor* (μ) of the tube. Thus if changing the plate voltage by 100 volts produces the same change in plate current as produced by a change of only 10 volts on the grid, the amplification factor is 10. When properly used, the voltage impressed on the grid of a tube will reappear in the output of the plate circuit with a new amplitude which approaches (but does not reach) the original amplitude multiplied by the amplification factor.

Tubes are usually designed so that when operated at their proper cathode temperature or voltage rating, further increase in temperature produces very little change in plate current. Then the grid has complete control over the plate current so long as the plate voltage remains unchanged. In practice the plate supply voltage is fixed and therefore the plate current varies as the grid voltage is varied as shown in Fig. 12.

This control electrode, or grid, takes very little or no current from the circuit to which it is attached. For this reason the power required to change the plate current, and thereby to initiate an industrial process, can be extremely small. However, the power output of the tube, or the power of the apparatus controlled by the tube, may be relatively large. Thus the tube's most important industrial application is its ability to amplify and to control power, *i.e.*, to permit small amounts of power to control the flow of large amounts of power.

The distinguishing feature of the high-vacuum tube is the complete control exercised over the plate current by the grid

voltage. In other tubes described later this control is not so complete; but in this latter case the type of tube in question
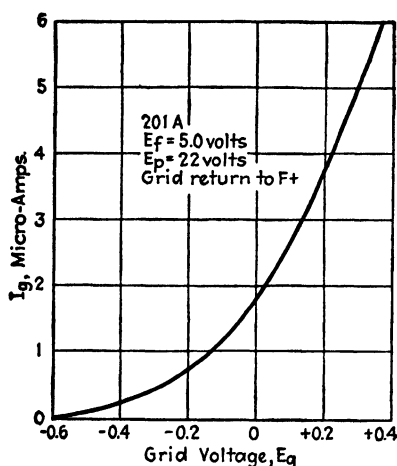

Fig. 11.—Grid current in typical tube. Grid connected to positive filament.
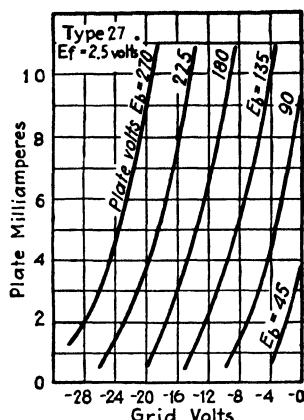

Fig. 12.—Family of plate-current grid-voltage curves.

will handle powers which make the high-vacuum tube rather insignificant.

HOT-CATHODE (THERMIONIC) TUBES*

	Number of electrodes				
	2-diode		3-triode	4-tetrode	5-pentode
General designation...	(Fleming valve)		(Audion amplifier)	(Screen grid)	(Suppressor-grid tube)
Control..............	Electro-magnetic	None	Electro-static	Electro-static	Electro-static
Vacuum........... .	Magnetron	Kenotron[1] Rectifier Phanotron[1] Rectifier Tungar[1] Rectigon[2]	Pliotron[1] Amplifier Thyratron[1] Grid-glow[2]	Photron[1] Amplifier Thyratron[1] Grid-glow[2]	Amplifier
Gas and mercury vapor					
High-pressure tubes...					

[1] General Electric designation.
[2] Westinghouse designation.
* *Elec. Eng.*, March, 1933.

Thus the high-vacuum tube grid has complete control over the flow of plate current; but the power-handling ability is relatively small. The gaseous tube grid, on the other hand, has much less control over the plate current, but the amounts of power under control are much larger.

Gaseous Two-element Tubes.—Introduction of the proper gas at the proper pressure into a tube of the general types described above changes the characteristics of that tube almost completely. Very large currents can now be sent through the tube; the voltage drop between cathode and anode becomes low
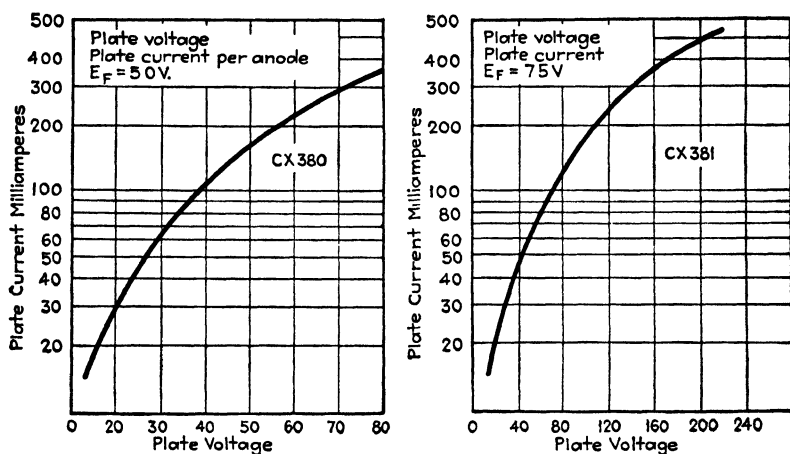

Fig. 13.—Characteristics of typical vacuum rectifiers.

and constant in value. In the gas tube, if it has a grid, there are no gradual modulations of plate current produced by variations in grid voltage. The plate current either flows, or it does not. If it flows at all, the magnitude of this current depends upon the external load, and upon the emission capability of the cathode, and to an extremely small extent upon the voltage on the grid, provided that voltage is of the proper value to permit any current at all to pass.

Consider, however, a two-element mercury-vapor tube. When the cathode is heated (it may be a filament or heater type) the metallic mercury vaporizes and the individual mercury molecules may be struck with sufficient force by electrons speeding toward the positive anode to disrupt the molecule and deliver from it an additional electron. This new electron

may take up its course toward the anode and thereby double the current-carrying properties. These electrons are probably removed from the outermost orbits far from the central nucleus.

But the production of additional carriers is not the only effect of ionization. The molecule after losing an electron is positively charged and will migrate toward the cathode which is negatively charged with respect to the plate. This positive molecule will neutralize part of the negative space charge which, in the high vacuum tube, limits the transport of electricity by electrons from cathode to plate. And this neutralization of the space charge is the more important function of the gas. Once this cloud of negatively charged particles is dispelled, and this takes but a microsecond or so, the current to the anode may rise to the full value permitted by the available emission.

Cathodes have been developed which will furnish 1,500 amp., and it appears that currents of the order of thousands of amperes are not impossible.

These heavy positively charged gas molecules may attain sufficient velocity toward the cathode to actually damage it upon impact. Many attempts to use gas to neutralize the space charge failed because of this destruction of the cathode. Then it was found that if the voltage across the tube was kept low enough, the ions did not attain a velocity great enough to damage the cathode. The voltage for disintegration is higher than that required for ionization; thus there is a fortunate margin of safety.

In the case of mercury-vapor tubes the voltage required to ionize the mercury is 10.4 volts, the actual voltage maintained across the tube is about 15 volts while the voltage required for disintegration is about 22 volts.

According to E. D. McArthur,[1] the mean velocity of a mercury atom in a container at 60°C. is 0.12 mile per second. An electron after acceleration by one volt has a speed of 368 miles per second. The mercury atom after being speeded up by falling through a drop of one volt has a speed of 0.6 mile per second.

Since a positive carrier moving toward the cathode is the equivalent, so far as current-carrying properties are concerned, of a negative carrier moving toward the anode, part of the total current flowing through the tube is carried by the gas molecules.

[1] *Gen. Elec. Rev.*, April, 1933.

But their speed is so small compared with that of the electron that only a fraction of the current is thus transported.

Pool-type Mercury-arc Rectifier.—The tubes so far described have been thermionic tubes; the electron stream has had as its source a heated filament or a heated surface coated with material which emits electrons at a fairly low temperature. The maximum current that can pass through these tubes is limited by the emission of the heated cathode, and although tubes are available in which this current may run to large values (several amperes) there are cases where much greater currents are desired. A new source of electrons is then desirable.

Such a source is a pool of mercury. If an arc is formed between this pool and another electrode, a cathodic spot is formed which furnishes the electrons. The spot dances about over the surface of the mercury, its size varying with the instantaneous current demands. Such a tube has certain advantages, chiefly the ability to withstand tremendous temporary overloads. These tubes are described in more detail later.

Comparison of Vacuum and Gaseous (or Vapor) Rectifiers.— The internal resistance of the vacuum tube is high compared with that of the gas-filled tubes. The gas tube, however, has a low internal resistance, and a constant voltage drop indicating that much better regulation is possible, *i.e.*, the output voltage is affected less by the current flowing than in the high-vacuum tube.

A high-vacuum tube has a life inversely proportional to its efficiency; the gas tube may have a long life and a high efficiency at the same time.

In general high-vacuum tubes have been used where small currents at high voltages are required; gaseous tubes are used for greater currents at low or high voltages. But these are general statements. The mercury-vapor tube is finding its way into installations where the vacuum tube was formerly supreme. Because of the greater efficiency and lower cost, it is probable that the gaseous rectifiers will supersede the vacuum type except for special cases.

The three-element high-vacuum tube, of course, will perform functions not possible by any gas tube produced to date. In these circuits it reigns supreme. Much work is being done with gaseous tubes to combine their features with those advantages

possessed, at present, only by high-vacuum tubes, and it is possible that amplifiers, oscillators, or modulators may ultimately be of the gaseous type.

Rectifier-filter System.—In Fig. 14 is a typical rectifier and filter circuit for producing direct current from an a.c. source. The tube conducts current during the half cycle when the anode is positive and does not conduct when the anode is negative. This produces bumps of current. These bumps of current flowing into the condenser charge it—but the peaks of voltage across the condenser *lag* behind the peaks of current into and out of it. These peaks of voltage force a current through the
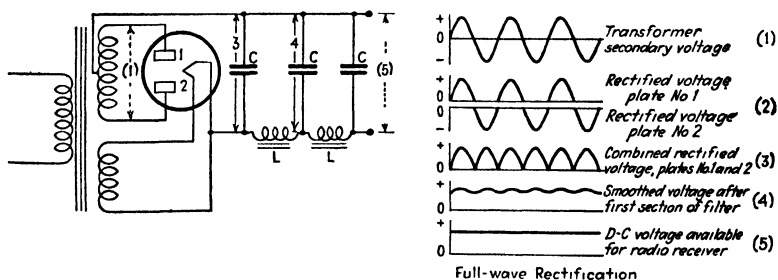

Fig. 14.—Full-wave rectifier using two tubes.   It is followed by a two-stage filter to produce direct current from alternating current.

inductances which tend to delay the rise and fall of current. The process may be visualized by imagining the condenser filling in the hollows of voltage and holding down the peaks; the inductance building up the hollows of current and holding down the peaks. Thus the condensers in the filter system tend to prevent change in voltage across the circuit; the inductances tend to prevent changes in current through the circuit. At the output terminals a uniform direct current is available.

Full-wave Rectifiers.—Tubes of the type so far described rectify only one-half of the a.c. cycle. With two such tubes, as shown in Fig. 14, both halves of the cycle may be rectified. This is known as *full-wave* or *double-wave* rectification. The two individual rectifiers can be put in one tube giving a full-wave rectifier in which one cathode furnishes the electrons for both anodes. Most full-wave rectifiers are of the high-vacuum type, although gaseous tubes which rectify both halves of the cycle have been put on the market.

Three-element Gaseous Tubes.—It might be supposed that if a grid is a valuable feature of a vacuum tube, it might be of importance in gaseous thermionic tubes. It is, indeed, but in a different way. The grid-glow tube (Westinghouse) and the thyratron (General Electric) are tubes of this type. Here the grid has a purely trigger function. It is able to start the current
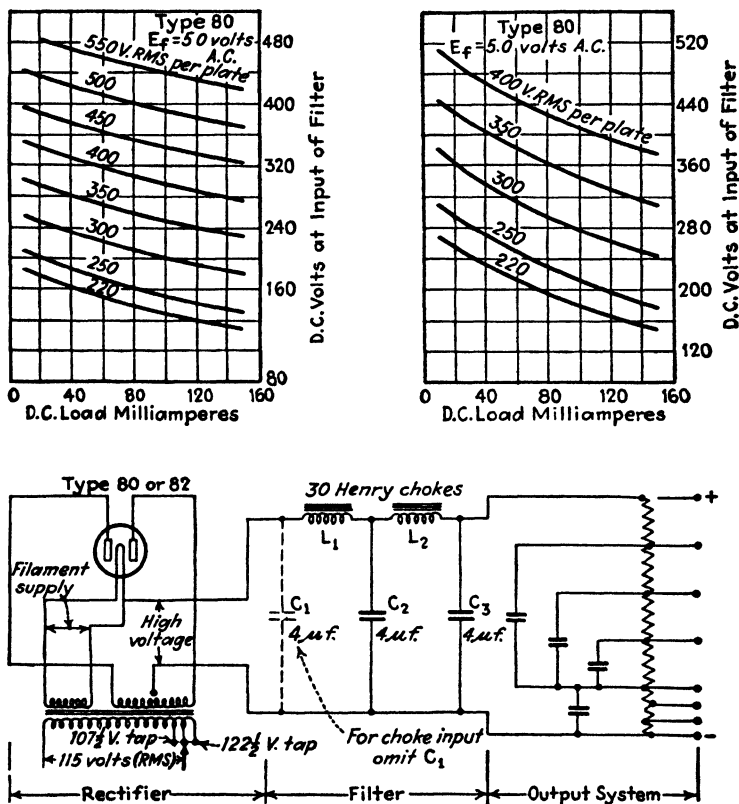

Fig. 15.—Circuit and output curves of full-wave rectifier. Left curves are for inductive input filter.

flow but it cannot stop it. In the high-vacuum case the grid has complete control over the current. In the gaseous triode, the grid has only limited control.

The features which make the gaseous rectifier important are again favorable to the gaseous triode. Large currents, high efficiency, low voltage drop, little power required to vary grid

voltages—all tend to make the gaseous triode of enormous industrial importance.

At low values of plate current the tube resembles a high-vacuum tube. As soon as the gas ionizes and appreciable current flows, however, the tube changes completely in its control characteristics. The moment sufficient current passes to ionize the gas, the grid is surrounded and its negative potential is neutralized by a sheath of positive ions. Then it no longer has any control over the plate current.

The current in this tube can rise almost instantly to its full value, limited by the emission of the cathode or the external resistance in the circuit. The tube, therefore, is a very sensitive current or voltage relay. Only a few microseconds may be required for the tube to operate once the proper grid voltage has been reached to permit plate current to flow. Thus if 10 volts negative on the grid will prevent current flow, a change of only 0.1 volt to 9.9 volts negative may permit ionization and a flow of plate current amounting to many amperes.
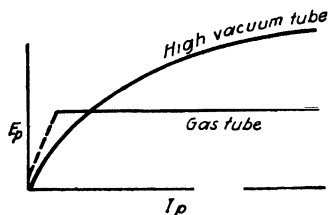
Fig. 16.—Comparison of gas and vacuum tubes.

Hundreds or thousands of amperes may thus be turned on by a fraction of a volt applied to the grid. But after the current is flowing, the grid is useless so far as further control is concerned. The only way to stop or control the anode current is to decrease or remove the anode voltage. This may be done in numerous ways to be described later.

A definite time, although very small, is required to de-ionize the gas when the anode potential is removed. This is a limiting feature of the gaseous triode. The vacuum triode easily follows voltages or currents of the order of millions of cycles per second; but the thyratron or grid-glow tube is limited in its control to frequencies of the order of a few thousand cycles. In industrial applications this is usually no disadvantage.

The characteristic of a typical grid-controlled rectifier of this general type will be seen in Fig. 17. Note that these curves, although resembling the characteristic of a high-vacuum tube are really quite different. In the latter case the curve will show

the relation between plate current and grid (or plate) voltage. Thus for each value of grid and plate voltage, for example, there is a given plate current. But in the case of the gaseous triode the curves show the values of grid and plate voltage at which the tube passes current. Thus with 2,400 volts on the plate for this particular tube, current will flow (the tube will "fire," as they say) when any grid voltage less negative than 5.5 volts is applied at a temperature 20°C. Any voltage more negative than this prevents current flow.
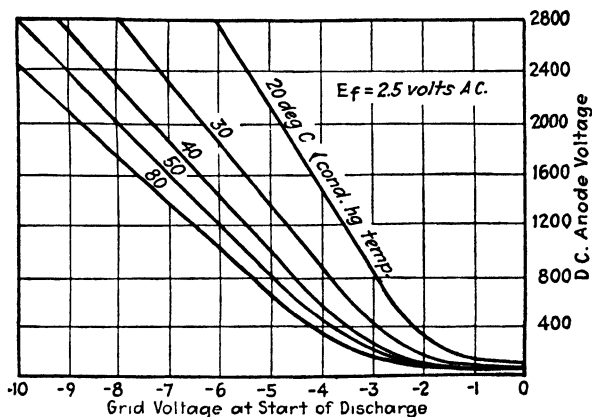

Fig. 17.—Characteristic of grid-controlled rectifier.

Multi-element Tubes. The Screen-grid Tube.—In addition to the control grid, other grids have been placed in the high-vacuum tube. The results are interesting and important. The first tube of this sort was the screen-grid tube. Later came the three-grid tube or pentode, and in 1933 came tubes with four and five grids.

In a triode, *i.e.*, a tube with a cathode, a grid and an anode or plate, an electrostatic capacity exists between each pair of elements. This is due to the fact that these elements are metallic and are insulated from each other. At low frequencies these capacities, *i.e.*, between grid and cathode, plate and cathode, and plate and grid, are of no great disadvantage. But if the tube is to be used at high frequencies, say of the order of several hundred kilocycles, the capacity between plate and grid causes trouble. At such frequencies this capacity has a sufficiently low impedance to couple the plate and grid circuits

together with an unwanted and uncontrollable coupling. This coupling is fixed; it is inherent in the tube structure.

At such frequencies the tube may no longer amplify properly; it may be unstable, particularly if high amplification per tube is desired. This instability comes from the following process. Suppose a small voltage is put on the grid. This is amplified and reappears in the plate circuit. If any part of this output voltage can get back into the grid circuit in the proper phase, it is again amplified and reappears in the output, or plate, circuit to augment what is already there. This feed-back of energy from a high-level source to a low-level point may continue until the circuit breaks into violent oscillation, which means simply that if the input voltage is normally secured from some external source, a.c. currents will continue to flow in the plate circuit even if this external source is removed. The tube has become a self-excited amplifier, or oscillator, and is no longer useful as an amplifier.

If an additional metallic grid or screen is put in the tube between the grid and the plate, and if this new electrode (called the *screen grid*) is grounded, the grid becomes effectively shielded from the plate and such unwanted coupling as described above is eliminated. Of course, it is impossible completely to shield the grid and plate; otherwise no input voltage would be amplified to reappear in the plate circuit; but in practice the effective capacity between grid and plate is reduced to a very low value. Thus in a triode the grid-anode capacity is about 5 to 10 $\mu\mu$f. In a typical screen-grid tube the value will be nearer 0.003 $\mu\mu$f.

This screening grid is, in practice, connected to some point in the power-supply system which is at a positive potential somewhat lower in value than the plate of the tube. It is, therefore, not at ground potential so far as direct current is concerned; but by means of other circuit elements this fourth electrode is grounded so far as the high-frequency signals are concerned.

The electrons speeding past the control grid come into the region of the positive screen grid where they acquire sufficient velocity to rush on through this field and land on the plate. The message they acquire in going through the field of the control (No. 1) grid is carried with them to the plate just as in a triode.

But the extra grid is not an unalloyed blessing. Since it is maintained at a positive voltage with respect to the cathode, it will attract electrons. If at certain instants of a.c. operation the plate voltage may be reduced to a potential lower than the screen, electrons will not go to the plate, or having once gotten past the screen grid and in the vicinity of the plate, they will turn about and return to the more positive screen grid rather than go on to the plate. Furthermore, if an electron shoots past the screen grid with sufficient velocity to knock another electron out of the plate, this electron will undoubtedly go to the screen because of its greater positive potential.
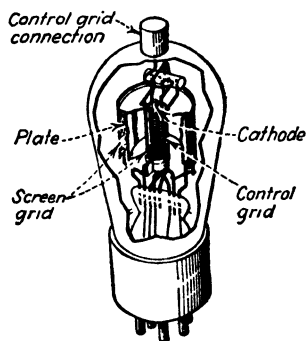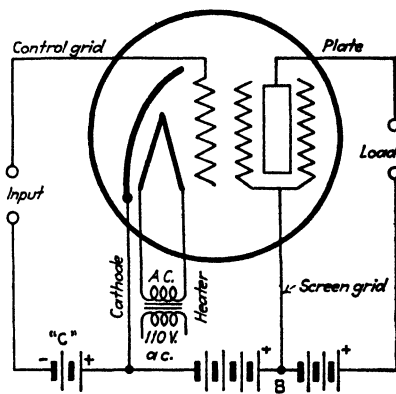

FIG. 18.—Screen-grid tube. FIG. 19.—Screen-grid tube circuit.

This effect causes electrons to go from plate to screen in the reverse of the proper direction. Thus in Fig. 20 it will be seen that at plate voltages lower in value than the screen the current actually decreases. Thus increasing the plate voltage from 20 to 60 causes a decrease of current from 3.5 to 2.8 ma. (with a control-grid voltage of zero). The tube is said to have a negative resistance because increasing the voltage causes the current to decrease.

Very little has been done to utilize this negative resistance region. Since it results from "secondary emission," *i.e.*, electrons released from the plate by primary or cathode electrons, and since the emission of such secondary electrons is an erratic performance, operation of tubes in this region is not so certain or so stable as in the normal region of positive resistance.

It will be seen later in this book that some uses have been found for the region in which increases in voltage produce a decrease in current; but in general screen-grid tubes are operated so that the plate is never permitted to go less positive than the screen.   Since the screen may have a voltage of 90 and the plate 250, it is seen that a portion of the characteristic is never utilized; *i.e.*, the plate may not be driven less positive than 90 volts by any instantaneous grid voltage.   The region from 90 volts positive to zero is not useful.

The screen-grid tube is a high-resistance tube.   Its internal resistance runs upward of one million ohms; triodes seldom have
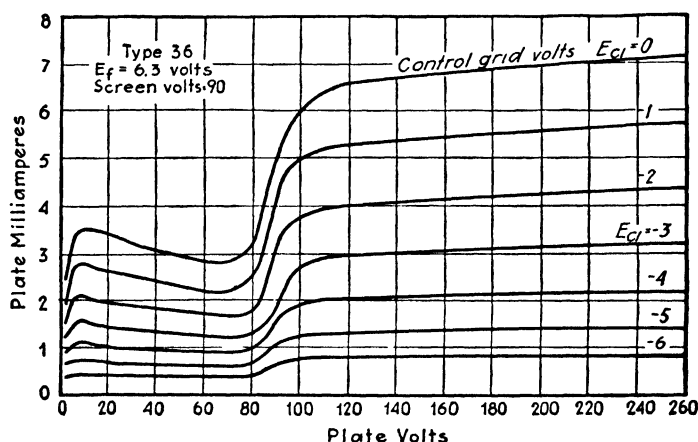

Fig. 20.—Characteristics of screen-grid tube.

resistance as high as 100,000 ohms and in general are of only a few thousand ohms.   Screen-grid tubes are used for voltage amplification only.   Triodes for voltage amplification have high resistances; power output triodes may have a resistance as low as 1,000 ohms.

The voltage amplification possible with a triode may be 20 with a high-mu tube (internal resistance of 30,000 to 100,000 ohms).   The voltage amplification possible with a screen-grid tube may be 200 to 300 under almost the same conditions. The latter tube, therefore, is a high-gain tube of high internal resistance and must be used in high-impedance circuits.

The Pentode.—Naturally it would be desirable if the wasted part of the screen-grid characteristics could be reclaimed.   A

three-grid tube, known as a pentode, makes this possible. The third grid is placed between the screen grid and the plate. This grid is connected to the cathode or to a point of zero potential. Now electrons accelerated by the positive potential of the screen dash through this zero-voltage grid and may drive electrons out of the plate. These secondary carriers find themselves in the field between the third grid and the plate. The plate is more positive than the third grid so that the third grid repels any electrons that may get free from the plate. They are driven back to the plate whence they came.
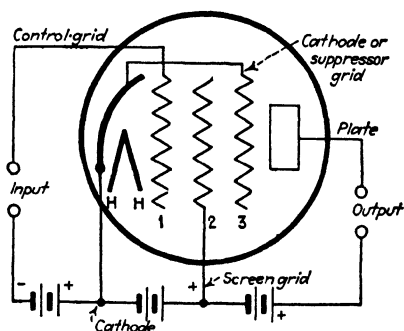

Fig. 21.—Circuit of pentode tube.

In such a tube the negative-resistance region is very largely or totally eliminated. The tube is still a high-resistance tube, compared to a triode (of the order of 60,000 to 100,000 ohms), but in the proper circuit will deliver a considerable quantity of power. The power pentode just described has a high amplification factor, of the order of 100, and to deliver a given quantity of power needs much lower exciting voltage on the control-grid circuit compared with a triode.

Thus a triode like the 45, which will deliver 1.6 watts to a load of 4,000 ohms, requires a grid excitation of 50 volts; a pentode like the 47 will deliver about the same power to the same load but requires only 13 volts on the grid to do it. The power pentode is thus a more sensitive amplifier than the triode. Pentodes have come into wide use for high-frequency amplification; here they are called *suppressor-grid* tubes getting their name from the common name of the additional grid.

There are other forms of multi-element tubes. In many cases economy has driven tube manufacturers, at the behest of radio-

receiver manufacturers, to combine in a single envelope two or
even more tubes.   Thus there are diode-triodes, triode-pentodes,
and other combinations.   These tubes do not operate any better
than two tubes, and in fact they usually represent a compro-
mise.   They save space and money; these are their only
recommendations.

Special-purpose tubes have been made with several electrodes,
such as those tubes used to change frequencies in a superhetero-

CAP INSULATOR
FERNICO EYELET
GRID LEAD SHIELD
GRID CAP
GLASS BEAD SEAL
VACUUM-TIGHT
STEEL SHELL
SUPPORT COLLAR
GETTER TAB
GLASS BEAD SEAL
FERNICO EYELET
PLATE INSULATING
SUPPORT
SHELL TO HEADER
SEAL WELD
HEADER
CRIMPED LOCK
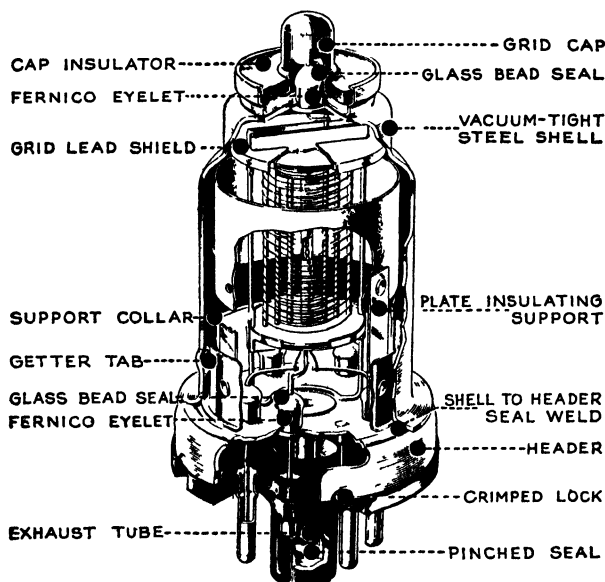EXHAUST TUBE
PINCHED SEAL

FIG. 22.—Details of metal-tube construction.

dyne receiver.   At present, the tendency seems to be toward more
and more complicated tubes.   In 1936 a tetrode was brought on
the market (the 6L6) which had the efficiency of the pentode
for power purposes, the low distortion of the triode.   In it,
use was made of the fact, fairly recently discovered, of the
importance of the spacing between cathode and anode and of
the experience gained in making cathode-ray tubes in which
electrons are forced to pursue definite paths by proper focusing.

Some experimental work has been done on types of tubes
in which the electron stream is controlled not by variations in
space charge but by actually deflecting the stream toward or away
from an electrode, similar to cathode-ray tube practice.   The

6L6-beam power tube is a first step in this direction in this country, and undoubtedly there will be many other examples as time and experience prove the virtues of new methods of stream control.

Metal Tubes.[1]—Most important from the industrial angle has been the development of the all-metal tubes, both for power purposes (large tubes) and for control purposes (small tubes). The tube-controlled welding apparatus described later in this book played a most important role in this new phase of tube design and manufacture.

The metal tube differs from the older art, as is well known, by having a metal envelope instead of glass. The tube elements are mounted differently, on much sturdier supports or in a totally different fashion (power tubes particularly), and the over-all appearance is more in the line of what an industrial engineer expects to find in factory apparatus.

At present, the tendency is for tubes to be placed in metal envelopes. It is doubtful if many industrial tubes will be placed in glass as time goes on and as designers learn the metal-tube art. The construction of a typical low-power receiving tube will be seen in Fig. 22 and of a rectifier for industrial purposes in Fig. 23.

Fig. 23.—FG-166, metal rectifier.

Short-wave Tubes.—The problem in generating currents of extremely high frequencies, say 30 megacycles or higher, has been the difficulty of getting tubes that had sufficiently low interelectrode capacity. This has been true of reception as well as of transmission. Since the capacity between electrodes goes down as the size of these electrodes goes down, tube designers have striven for smaller size. Furthermore, if the spacing between cathode and anode and other elements is decreased at the same time the other dimensions are reduced, the voltage amplification
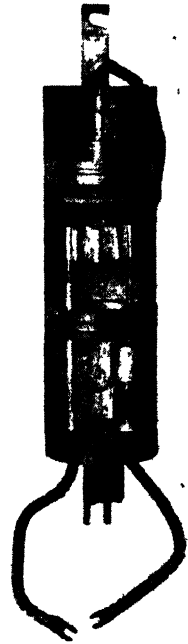
[1] On metal tubes see *Electronics*, April and May, 1935; and *Gen. Elec. Rev.*, October, 1934, and May, 1935.

and mutual conductance of the tube will not differ much from tubes larger in size.

The acorn type of tube brought out in 1935 by RCA and somewhat similar tubes developed by the Western Electric company are good examples of design in this direction.

On the other hand, it has been determined by Harries[1] of England that high-impedance tubes can be built in which the control value of the grid is as great as in present types even though a very great distance exists between cathode and anode, with the control grid near the cathode. He has found that a critical distance exists and that if the anode is placed at this distance,
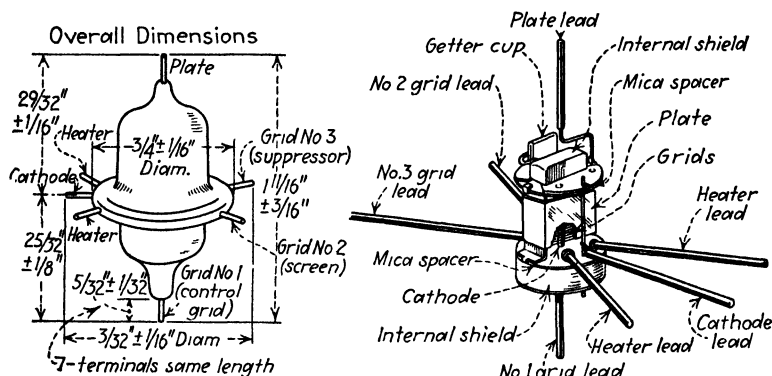

Fig. 24.—Construction and dimensions of acorn tube.

a perfectly good workable tube results but that the grid-cathode capacity is decreased to a very great extent. He has made short-wave tubes of this type. No doubt further research and commercial design will develop this principle still further.

Voltage-regulator Tubes.—Two types of tube for use in power-supply circuits are available. One is a tube which has a constant voltage drop across it, unaffected (within limits) by the current through it. In operation the tube glows with the color characteristic of the gas within it. The UX-874 is representative of this tube.

The other type of tube has a constant current through it regardless of the voltage across it. It is used in series with the primary of a power transformer holding the voltage across the

[1] HARRIES, J. H. O., *Electronics*, May, 1936, and *Wireless Eng.*, April, 1936.

secondary of the transformer constant, regardless of the voltage variations in the primary circuit.

Cathode-ray Tubes.—Still another type of tube which will become increasingly important commercially and in industrial plants is the cathode-ray tube, at the moment largely used in laboratories for studying periodic or rapidly changing voltages or currents, such as transients, or sine waves of various frequencies, or waves of various harmonic contents.

It is a development of the Crookes tube in which a stream of electrons is directed toward one end of the evacuated tube. Objects placed in the path of these electrons will cast a shadow. The phenomenon attracted the attention of many scientists of high rank; their research finally developed that the rays emanating from the cathode were particles of matter later to be known as electrons. It was discovered that these particles could be deflected in magnetic and electric fields. From the dimensions of the tube, the voltage across its terminals, and the deflection under known magnetic and electric forces the ratio of the charge to the mass of the particle (the electron) was worked out.

The cathode-ray tube of today is a thermionic tube contrasted with the earlier Braun tube which had a cold cathode. The filament furnishes the electrons which are drawn by a high voltage toward the large end of a glass envelope where they strike a screen of fluorescent material. En route the line of flight, the electrons are deflected by magnetic coils or electrostatic plates changing the point on the screen where the electrons strike. When the electrons hit the screen material, they give up their kinetic energy causing the screen to glow with a visible light for a period, long or short, depending upon the material on the screen, the speed of impact and the degree of concentration of the beam.

Thus by deflecting the electrons, a visible pattern picture of extremely high speed and complicated electrical wave forms can be obtained on the screen. A more extended description of the cathode-ray tube will be found later.

X-ray Tubes.—When high speed electrons strike a metallic target and deliver their energy there, radiation of very short wave length is given off. These light waves are known as Roentgen or x-rays. Whereas the cathode rays are really streams of particles of matter with definite mass, x-rays are truly

like waves of light, too short in length to be visible to the eye, but possessing all the other attributes of light waves. So short is the wave length of these radiations that they will pass between the lattice-like structure of the elements and compounds, but when they occasionally strike an atom they are deflected just as a light wave is deflected by a material object in its path.

A photographic plate is sensitive to x-rays. Therefore, if some dense object is put between the plate and the source of radiation, a shadow will be cast. Denser objects will cast heavier shadows. The x-ray tube, therefore, is useful in examining objects like metal castings or the bones of the human body that are opaque to visible light.

Since the x-rays are reflected from atoms, the lattice structure of the atom has the same effect on x-rays as a diffraction grating on light waves. From the pattern which the diffracted x-rays make upon a photographic plate an accurate determination of the lattice dimensions and arrangements of the atoms in this element or compound may be obtained.

The x-ray has become an important tool of the engineer as well as the physicist, chemist, metallurgist, physician, and others interested in shadowgraphs of more or less dense objects either with the idea of detecting flaws or foreign matter in the objects, or interested in quantitative analysis of compounds or unknown substances.

Secondary Emission Tubes.—Two investigators widely known for their research into television, P. T. Farnsworth and V. K. Zworykin, have developed interesting types of tubes known as electron multipliers. Both utilize the phenomenon of secondary emission whereby an electron, striking a positively charged target, causes it to emit other electrons, sometimes in the ratio of 8 or 10 to 1, compared to the primary electron. These secondary electrons may in the case of Farnsworth's tube, be caused to strike again the first target by means of a high-frequency field or in Zworykin's tube, may be caused to strike a second target by an electrostatic field producing from it another batch of electrons, amounting to eight to ten times the number secured from the first target. This process may keep up through 10 or more stages, producing a current amplification of perhaps 8^n, where n is the number of multiplier stages.

These tubes are essentially amplifiers of current, not voltage. The use to which they will be put, outside communication, has not been clearly seen up to this time.

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CHAPTER III

VACUUM-TUBE AMPLIFIERS

The function performed by two-element thermionic tubes is that of *rectification*, the translation of alternating current into unidirectional pulsating current which can be smoothed by means of capacities and inductances so that it finally has all the characteristics of current generated by a battery or by a commutated rotating machine; it no longer reverses its direction but flows continuously at uniform voltage.

The function performed by the three-element tube, the triode, is that of *amplification*. By this process is meant the release of power from a local source by means of a very much smaller expenditure of power controlled by some actuating force. Thus the tube is in reality a relay, but of much broader accomplishment than a mechanical relay.

The vacuum-tube amplifier really does much more than release power from a local battery when the grid circuit of that tube is excited by a voltage. But because of this ability to amplify or release power, many other most important functions become possible; to cite but one example, the conversion of battery power (d.c.) into alternating-current power of pure or distorted wave forms of frequencies as low as a few cycles per minute to as high as many millions per second, and in amounts up to hundreds of kilowatts.

Therefore it is of fundamental importance that the phenomenon of power amplification by means of high-vacuum thermionic tubes be well understood. Of course, it is possible to amplify voltage or current as well as power, but the general term, power amplification, includes all manner of amplification described below.

Mechanism of Amplification.—The triode is nearly always operated with a constant cathode temperature. This cathode can be either a filament or a surface heated by a filament, although not necessarily in electrical contact with it. The

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cathode temperature is sufficiently high that with the plate and grid voltages used, increasing the temperature by increasing the cathode voltage would not result in a useful increase in tube current.

Therefore in the normal operation there is a fixed and, for practical purposes, constant supply of electrons. Two factors can change the number of these electrons that reach the plate, *viz.*, the voltage on the plate with respect to the cathode, and the voltage on the grid with respect to the cathode. Thus changing the plate voltage by 100 volts may produce a plate current change of 10 ma. A grid-voltage change of only 10 volts may produce the same change in plate current. Therefore the grid is obviously ten times as effective.

Suppose then, a triode is connected as in Fig. 1, where a load (indicated by the resist-

Fɪɢ 1 —Fundamental amplifier circuit.

ance R_0) is in the plate circuit between tube and battery.
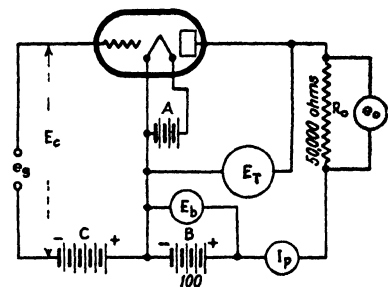
This is the fundamental high-vacuum-tube circuit. Note that there are three sources of power. The *A battery* which heats the cathode or filament, the *B battery* which maintains the plate at a positive potential with respect to the filament, and the *C battery* which maintains the grid either positive or negative (usually the latter) with respect to the cathode. The A battery is a low-voltage–high-current source, the B battery is a high-voltage–low-current source, and the C battery furnishes voltage only since, normally, no current is taken by the grid.

Neglecting for the moment that the electrons actually move from cathode to anode, and considering an electric current as flowing from a positive to a negative direction (according to convention), the current from the B battery flows to the plate through the load or work circuit, then to the cathode across the vacuum in the tube, and returns to the B battery through the filament. Therefore the plate current flows through the filament while the filament current does not flow through the plate circuit. In general, however, this additional current through the filament

due to the plate current is small compared with the filament-heating current.

In the 27, a typical three-element amplifier tube, the current heating the filament is 1.75 ampere; the maximum plate current is seldom over 10 ma.

In Fig. 1 the terminal voltage of the B battery is 100 volts, the resistance is 50,000 ohms, and the plate current flowing is 1 ma. The voltage drop along this resistance is
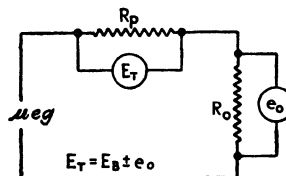
$$E_0 = I_p \times R_0 = 0.001 \times 50,000, \text{ or}$$
$$50 \text{ volts.}$$

FIG. 2.—Equivalent tube circuit—a generator in series with two resistances.

The voltage E_T actually between plate and cathode is 50 volts. This may be represented in Fig. 2 where R_p is the resistance of the tube and R_0 is the resistance of the load.

Now suppose by changing the grid voltage by 1 volt, the plate current becomes 0.0013 amp. and the corresponding drop along R_0 becomes 65 volts, a change of 15 volts. Thus a change
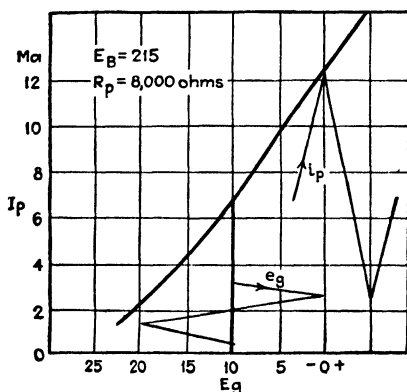

FIG. 3.—Variation of plate current with changes in grid voltage.

of one volt on the grid has produced a change of 15 volts across the plate load—a voltage amplification of 15.

As another example suppose that a tube and its load have a characteristic like that in Fig. 3 and that the grid be biased by a C battery by −10 volts. This means that the grid is negative with respect to the cathode by 10 volts. With no other voltage

applied to the grid the plate current through an 8,000-ohm load is approximately 7 ma., and the voltage drop across the 8,000-ohm load will be 56 volts.

Now suppose the grid voltage E_g is varied in steps, for example, up and down from -10 volts. With -10 volts, the plate current will be 7 ma. (Fig. 3), and the voltage across an 8,000-ohm load will be 56 volts. If the grid voltage E_g is changed to 0 volts, *i.e.*, 10 volts less negative than it was at -10 volts, the plate current becomes 12 ma., and the voltage drop along the load resistance will be 96 volts. The portion of the battery voltage E_B that will appear across the tube itself in these two conditions will be respectively, $215 - 56 = 159$ and $215 - 96 = 119$ volts.

Thus by changing the grid voltage by 10 volts (from -10 to 0 volts) the voltage across the load resistance has been changed from 96 to 56, or a change of 40 volts. Therefore, the effective voltage amplification of the tube and circuit is 4.

If the grid voltage is varied according to a sine wave, sine waves of current change will occur in the plate circuit and sine waves of voltage will appear across the load resistance. An a.c. voltmeter would show this voltage if placed across the load.
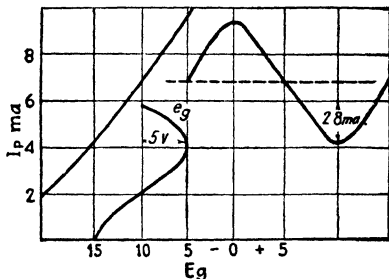

Fig. 4.– Sine-wave plate current due to sine-wave grid voltage.

In Fig. 4 for example, a peak voltage of 5 a.c. on the grid produces a peak plate current of 2.8 ma. through an 8,000-ohm load; or a voltage of 23 volts alternating current approximately across the load.

Note that subscripts indicate the voltage or current under consideration, thus E_g stands for grid voltage, E_p for plate voltage, I_p plate current, etc. Caps indicate steady or d.c. values; small letters indicate a.c. values. Thus E_c is the grid voltage due to the C or bias battery, e_g is an input a.c. voltage.

It should be pointed out at the outset that the grid circuit is almost an open circuit. Power can flow from cathode to anode because of the thousands of carriers (electrons) flowing from cathode to anode. But none, or at least very few, flow to the grid. The grid is merely a control electrode, nearly always maintained negative with respect to the cathode, and therefore it actually repels electrons from it. The degree with which it repels the

electrons controls the space charge which prevents electrons from reaching the anode.   But since very few electrons find their way to the grid, the current in the grid-cathode circuit is extremely small.

Such is the process of amplification.   A voltage on the grid is repeated, enlarged in amplitude, in the plate circuit.   When the grid becomes positive (or less negative than it was), more plate current flows, and the voltage drop along the load is greater. Then when the grid becomes more negative, the plate current decreases, and a smaller voltage drop appears across the load. Thus the grid and load a.c. voltages are in phase, a decrease in e_g producing a decrease in e_0.
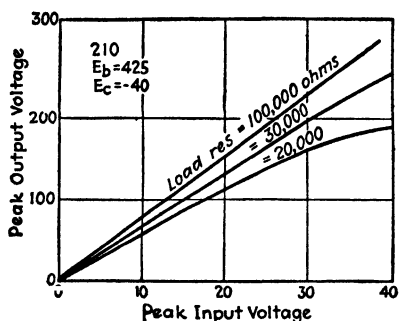

Fig. 5.—Effect of increasing load resistance in increasing amplification.

Because the current taken by the grid may be very little, only a few microwatts may be consumed in the grid or control circuit.   On the other hand, high voltages and currents may be in the plate circuit, always under complete grid control.   The amplification of power, *i.e.*, the ratio of power in the load to the power applied to the grid circuit, may be very great.

A mechanical or electrical relay merely opens or closes a circuit. A vacuum tube not only causes a current to flow or cease flowing in a circuit, but it can control the value of that current in steps infinitesimally small.   This control may be exercised in a millionth of a second, or it may be repeated a million times a second.   The tube never hesitates; it will continue its control for several thousand hours, and it is simple to replace.

Amplification Factor.—The voltage amplification in a tube depends solely upon the construction of the grid and the relative distances between the cathode and the grid and the cathode and the plate.   If the grid is wound closely and is close to the cathode, it will have a greater effect upon the plate current than if it is a coarse mesh or pitch and is situated farther from the source of electrons.

Considering the circuit as a whole, *i.e.*, tube plus load, the amplification depends upon the amplification factor of the tube and the relation existing between the internal resistance of the

tube and the external resistance in the plate circuit, that is, the load resistance. [This is not strictly true. The amplification factor of even well-made tubes falls off at high negative grid voltages. Thus the amplification factor (often called by the symbol μ) is not strictly a constant; and for some purposes this change in the mu factor of a tube must be taken into account.]

The equivalent circuit of a tube and its load may be represented as a voltage in series with two resistances as in Fig. 2. Here the voltage μe_g is actually the voltage e_g put on the grid, multiplied by the voltage amplification factor μ of the tube. The voltage that will appear across the load will depend upon the resistances and the amplification factor according to

$$e_0, \text{ load voltage, } = \frac{\mu e_g R_0}{R_0 + R_p}$$

The effect upon the voltage amplification of the circuit and tube as the load resistance is varied will be seen in Fig. 6 where it is shown that the greater the load resistance

FIG. 6.—Amplification as a function of load resistance.

compared to the internal resistance of the tube the greater the amplification. If $R_0 = 3R_p$, 75 per cent of the mu of the tube will be realized.
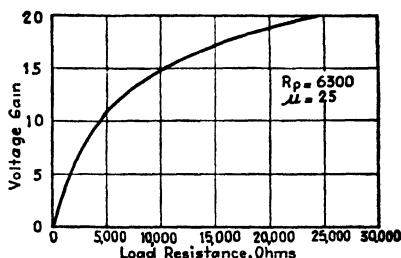
Tube Plate Resistance.—Consider the family of plate-voltage plate-current curves in Fig. 7. These curves all have identical slopes which means that equal changes in plate voltage produce equal changes in plate currents. The ratio of such changes is known as the internal plate resistance of the tube. Thus

$$\text{Plate resistance, } R_p = \frac{\Delta E_p}{\Delta I_p},$$

where Δ indicates "a small change in."

This is not the same as the d.c. resistance of the tube, calculated by dividing the plate voltage by the plate current. The internal resistance that is used in calculating circuit problems is the *dynamic resistance* R_p or the resistance to variations in current and voltage given above.

In general, tubes with low internal resistance are tubes with low amplification factors.   The ratio of amplification factor to plate resistance for the smaller tubes is about 0.001; therefore
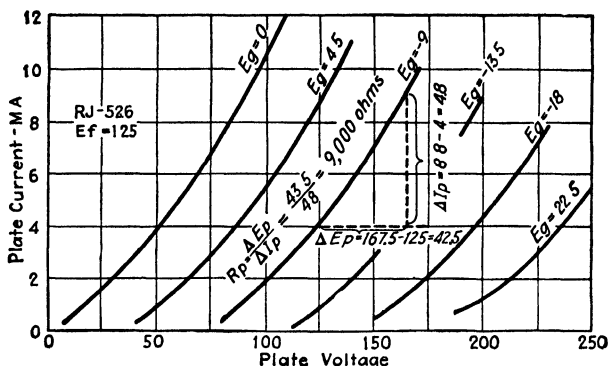

Fig. 7.—Calculation of plate resistance, $\dfrac{\Delta E_p}{\Delta I_p} = \dfrac{43.5}{0.0048} = 9,000$ ohms.

the greater the amplification factor the greater is the resistance. Tubes of low mu factor are used to control or amplify considerable power, tubes with high mu are used almost solely as voltage amplifiers.
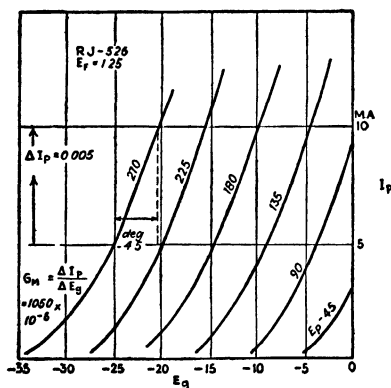
Mutual Conductance.—The factor which shows the grid voltage required to vary the plate current a given amount is the *mutual conductance* (G_m) more recently called the *transconductance*.   In Fig. 8 G_m is the slope of the I_p-E_g curves. In the average small tube used for radio-reception purposes this factor is about 0.001 mho (1,000 micromhos) indicating that a change of 1 volt on the grid produces a change in plate current of 1 ma.   Power tubes and large tubes may have much greater mutual conductances, often as high as 5,000 micromhos.

Fig. 8.—Calculation of mutual conductance.

The amplification factor of a tube is more or less independent of the voltages used on the grid and plate.   On the other hand,

the plate resistance increases for low values of plate voltage and for high negative values of grid voltage. And because G_m is numerically equal to μ/R_p it increases with low negative grid voltages and high plate voltages. These variations are shown in Fig. 9.
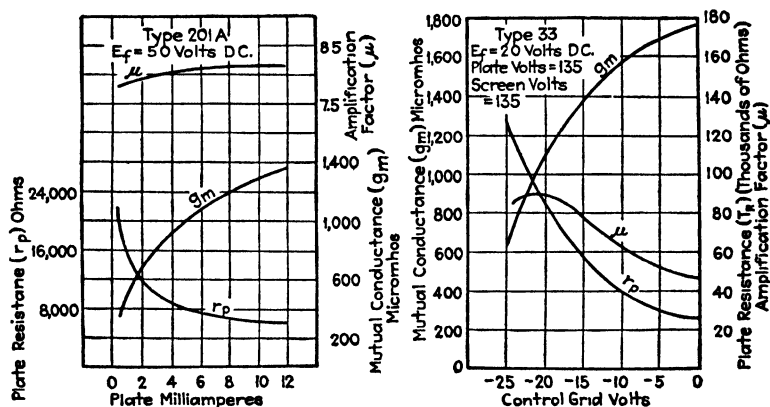

Fig. 9.—Variation in tube constants with plate current or grid voltage.

Power Output.—When the greatest amount of voltage amplification is desired, the formula shows that the load resistance across which the amplified voltage is to appear must be high compared to the internal resistance of the tube. So in radio circuits where a few microvolts are taken from the antenna-ground system and amplified to the point where 50 or more volts appear across a detector circuit, very high resistances are used in the plate circuits. Up to the detector which separates the modulation from the carrier, bringing voice and music to the receiver, high-mu tubes designed solely for voltage amplification are used.

When a tube is to amplify voltage, it works into a high-resistance load. If, on the other hand, current is to be amplified, the tube works into a very low resistance. A power amplifier works into medium resistances, usually of the order of a few thousand ohms. A voltage amplifier has applied to it small grid-voltage variations; a power amplifier has large voltage variations impressed on the grid-cathode input circuit.

In industrial applications the input voltages are usually higher, but the power available is small. Out of a photocell, for example, as much as 10 or more volts may be secured by

causing the current to flow through a high resistance. This voltage impressed on a power tube will release a power of upward of 1 watt or more, which is sufficient to operate a relay immediately. This relay may control several hundred watts or in turn may control other relays opening or closing circuits in which an unlimited amount of power may be flowing.

When a tube is to deliver power, the same rule holds as in any circuit where energy is to be transferred from a source to a load. The greatest amount of transfer will take place when the
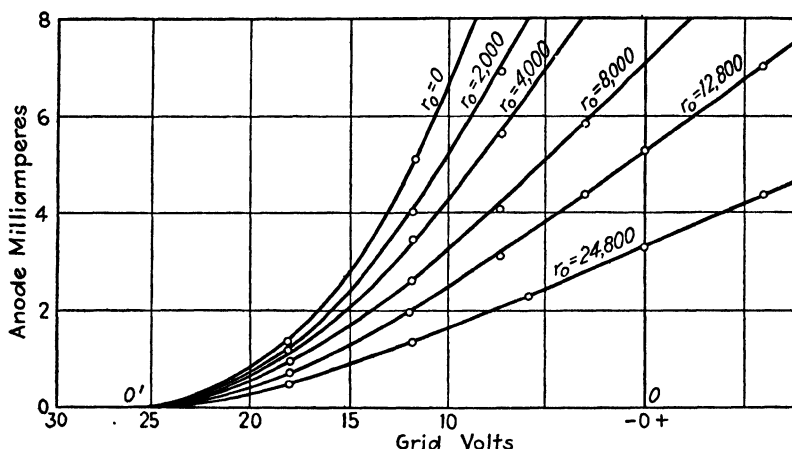

Fig. 10.—Effect on characteristic curves of placing a load in plate circuit.

load resistance is equal to the internal resistance of the tube. Then the power will be

$$\frac{\mu^2 e_g^2 R_p}{4R_p^2} \quad \text{or} \quad \frac{\mu^2 e_g^2}{4R_p}$$

and under any condition the power will be

$$\frac{\mu^2 e_g^2 R_0}{(R_0 + R_p)^2}$$

where e_g = r.m.s. input voltage.

The load resistance can differ appreciably from the tube resistance before much power is lost. Figure 3, Chap. I, shows the relation between power and the ratio between load and tube resistance.

Dynamic Tube Characteristics.—In giving the characteristics of tubes so far, the relation between the plate current and the

grid, or plate, voltage without any load in the plate circuit has been given. These are called *static* characteristics. Similar curves showing the plate current for each value of grid or plate voltage when a load is in the plate circuit are called *dynamic* characteristics.

In the process of amplification, as explained above, some voltage drop occurs across the load resistance and therefore some voltage must be momentarily subtracted from that existing between cathode and plate. Since at this moment there is a lower plate voltage, the plate current must be lower. Therefore the static characteristic does not give a true picture of the manner in which the plate current is dependent upon grid or plate voltage when a load resistance exists in the plate circuit.

Determination of Power Output.—The diagram shown in Fig. 11 has become the standard method of calculating the power output, the voltage across the load, and the current through the load. The procedure is as follows: It is decided to operate the grid with a bias of -80, a plate current of 22.5 ma. (or with a plate voltage of 350), and with a load resistance of 15,000 ohms. The problem is to determine the power into this load when the grid is excited with a peak a.c. voltage of 20, and to find the a.c. voltage across the load, and the a.c. current through it.

The line AB is called the load line. It is drawn through the $E_c = -80$ line at the point where it crosses the desired value of I_p, *i.e.*, 22.5 ma., or at the place where it crosses the $E_p = 350$-volt line. This load line must be such that its slope is equal to the load resistance. Thus the slope of the line $R_0 = E_p/I_p$. The simplest method of drawing this line is to draw first a line with the desired slope from the $E_p = 350$ volt-zero current point D to the point on the current axis given by dividing E_p by R_0, in this case 350 volts by 15,000 ohms or 23.5 ma. Then the load line AB is drawn parallel to CD.

On the diagram is shown the $e_g = 20$ volt (peak)-variations, and the resulting variation in i_p and e_0 also in peak values. This shows that the peak plate current through the load will be 3 ma. and the peak a.c. voltage across the load will be approximately 50 volts. The power through the load will be, therefore,

$$\text{Power in load } \frac{i_p}{\sqrt{2}} \times \frac{e_0}{\sqrt{2}} = \frac{i_p e_0}{2}, \text{ or 75 mw. approximately.}$$

The plate battery required to insure that the plate actually gets the desired 350 volts may be determined by prolonging the load line until it crosses the plate voltage axis. In this case this would be approximately 640 volts. The d.c. voltage on the plate would then be 350 volts, and the d.c. voltage across the load would be $640 - 350 = 290$ volts.
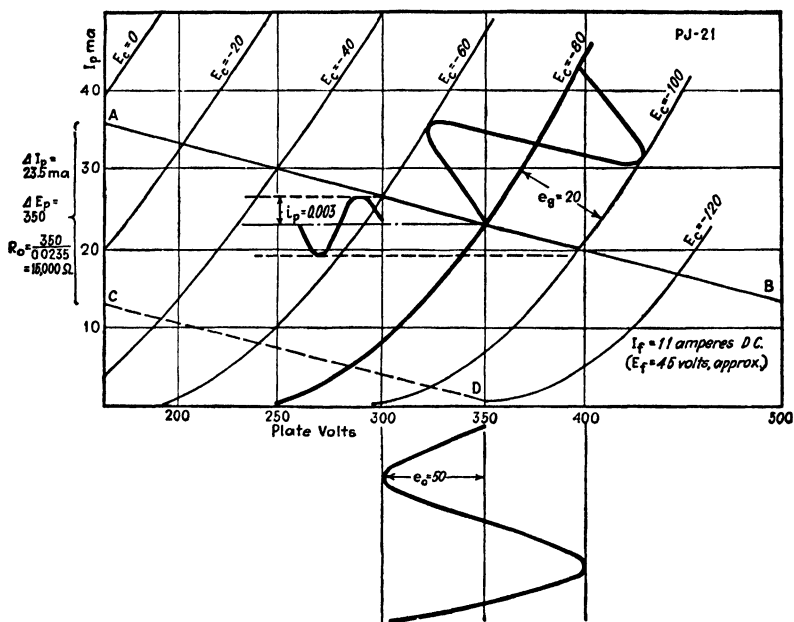

FIG. 11.—Determination of power output.

As a check on this calculation, the values of input voltage, load and tube resistance and mu factor (3) may be fitted into the equation already given for calculating power output. Thus

$$P_0 = \frac{\mu^2 e_g^2 R_0}{(R_0 + R_p)^2} = \frac{9 \times \left(\dfrac{20}{\sqrt{2}}\right)^2 \times 15{,}000}{(15{,}000 + 3{,}150)^2}$$

$$= \frac{9 \times 200 \times 15{,}000}{(18{,}150)^2}$$

$$= 82 \text{ mw.}$$

This is close enough as a check upon the two methods. The load-line method is more accurate. From it can be determined

the percentage distortion, if desired. This value, however, is of little interest in the design and operation of industrial amplifiers.

Types of Amplifier Circuits.—The grid-cathode path of a vacuum tube is a high-resistance circuit, of the order of many megohms if the grid is negative. On the other hand, the plate-cathode path is much lower in resistance, of the order of thousands of ohms. The tube, therefore, is very useful in connecting a high-resistance device to a low-resistance circuit. The average power relay has a resistance of the order of from a few ohms to a few thousand ohms. The photocell, on the other hand, has a resistance of megohms. While the voltage output of the cell may be up to 30 volts, the resistance of the relay is so low, it would short-circuit the photocell if placed directly across it, and, of course, the relay would not operate. This means simply that the photocell cannot deliver sufficient power to operate a low-resistance relay. (But see Chap. VI.)

If the photocell changes the grid voltage of a tube, the plate current of the tube will operate the relay. The tube has acted as a transformer in which not only the voltage but the current has been stepped up. The circuit is shown in Fig. 12. The current through the resistor is, say, 10 μa. The power taken from the cell is 100 microwatts, the voltage across the resistor is 10 volts. This 10 volts will cause a plate current of 10-ma. plate current to flow if the mutual conductance of the tube is 1,000 micromhos and if the resistance of the relay is 2,000 ohms or less.

FIG. 12.—Phototube operating relay by means of an amplifier.

This current flowing through the 2,000-ohm relay produces a voltage of 20 volts, and the power transferred to the relay is 200 mw. In this case the power amplification is

$$200 \times 10^{-3} \div 100 \times 10^{-6} \text{ or } 2,000 \text{ times.}$$

Alternating-current Amplifiers.—If an alternating current is to be amplified, there are several circuits possible. The alternating current may flow through the primary of a trans-
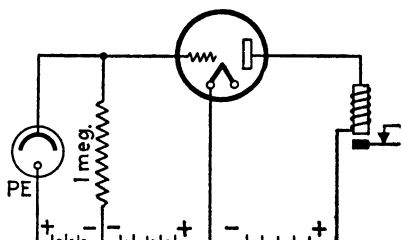
former whose secondary is connected in the grid-cathode path
of the tube, as shown in Fig. 13. Two tubes may be connected
to each other by means of a transformer, the primary being in
the plate circuit of one tube and the secondary in the grid circuit
of the following tube. The turns ratio of the transformer is
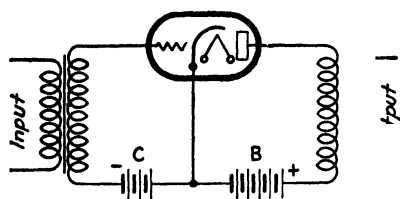adjusted so that the greatest amplification is secured. If ampli-
fication over a narrow band of
frequencies is desired, say at 60
cycles, or at 1,000 cycles only,
the ratio of turns between
secondary and primary can be
high, 10 or more. If the band
of frequencies is wide, for
example, in an amplifier for
voice or music frequencies, the turns ratio will be small (from 2
to 5) because of the difficulty of making high-ratio transformers
which will amplify a wide band equally.

Fig. 13.—Transformer-coupled amplifier.

In such an amplifier all stages but the final are used for pro-
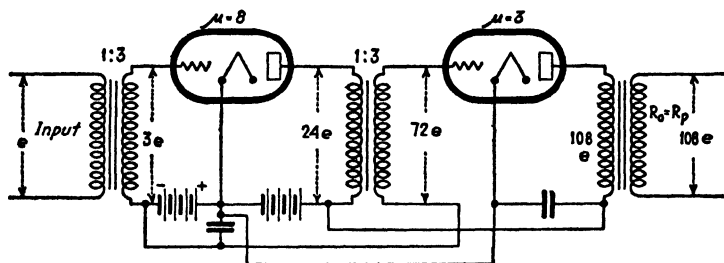ducing voltage amplification. Tubes with fairly high amplifica-

Fig. 14.—Amplification of voltage in two-stage circuit. One-half the final
voltage appears across the tube and one-half across the load.

tion factors (8 to 12) are used. The final stage, however,
must supply power to accomplish the final aim of the entire
system. The final tube, therefore, has a lower mu (2 to 4) so
that the current flowing in its circuit will be fairly large without
using high plate voltages.

Another type of coupling is the resistance-capacity system
shown in Fig. 15. This is used where a wide band of frequencies
is to be transmitted without distortion, *i.e.*, all frequencies
are to be given equal amplification. The resistance R_0 plays
the part of the coupling impedance and across it the output

voltage is developed. This voltage is impressed on the following tube through the condenser C which prevents the plate voltage
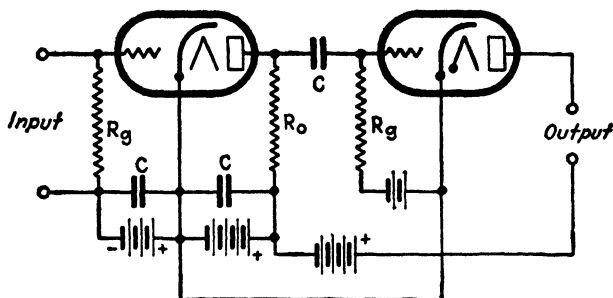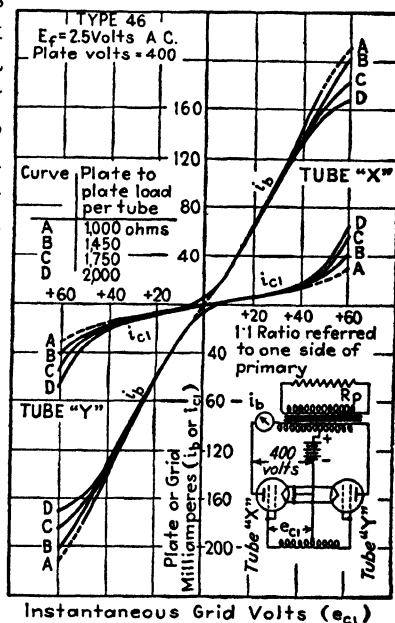

Fig. 15.—Resistance-capacity coupled amplifier.

on the first tube from being impressed on the grid of the second tube. To maintain the grid-cathode path of the second tube at a high resistance, this grid is biased through a grid-leak resistor R_g of the order of a megohm. The condenser may have values between 0.006 to 1.0 μf depending upon the band of frequencies to be transmitted. The circuit uses tubes of high mu (30 or more) and there is no voltage step-up in the inter-tube coupling system.

Types of Amplifiers as to Wave Form.—If the grid of an amplifier tube is biased negative properly and if the input voltage is not too great, the output voltage will have almost exactly the same form as the input. This is distortionless amplification. The method of operating a tube and circuit in such a manner is called *class A amplification*. So long as the

Fig. 16.—Operation of tubes in class B circuit. (*RCA Radiotron Handbook.*)

input peak voltage does not cause the grid to go positive or cause the plate current to traverse the lower curved part of the I_p-E_p

characteristic on the negative half cycles of grid voltage, amplification will be essentially distortionless.

In class A amplification the efficiency (not counting the power used to heat the cathode) cannot be greater than 50 per cent, and actually runs about 25 per cent, where the second harmonic of the input wave generated in the amplifying process is not greater than 5 per cent (an arbitrary figure taken as the criterion of distortionless amplification).
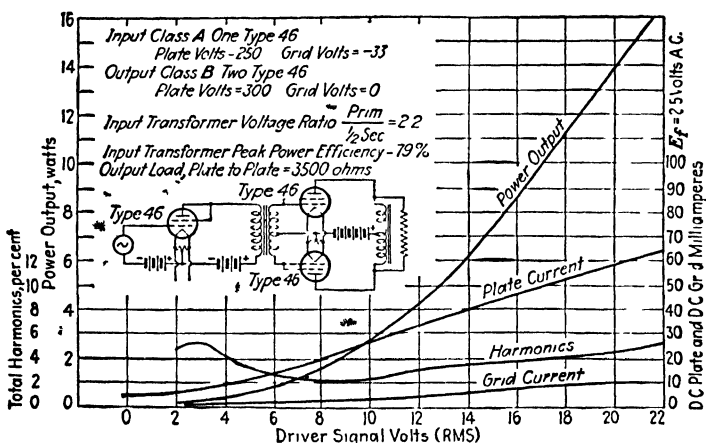

Fig. 17.—Class B characteristics.

In class B amplification the grid is so biased that little plate current flows during the negative half cycles of input signal. The grid may go positive. Class B characteristics are shown in Fig. 17. Such an amplifier generates considerable second, and other, harmonics. These are removed from the output by suitable means if such an amplifier is to be used for speech or music. The amplifier is more efficient than class A.

In class C amplification the grid is made so negative that the plate current is zero with no excitation and flows only when the

COMPARISON OF AMPLIFYING SYSTEMS

Class	Efficiency	Distortion	Power output proportional	Power amplification
A	Low	Low	$e_g{}^2$	High
B	Medium	High	$e_g{}^2$	Low
C	High	High	$e_p{}^3$	Low

grid is driven positive by the input signal. Such a circuit is highly efficient, as high as 85 per cent and, of course, distorts the input signal. This distortion is removed in the output by various means.

Tubes operated in class B amplifiers for audio-frequency work are never used singly; they are used in a push-pull circuit. In this case the even harmonics are balanced out so that only the fundamental remains. Class C amplifiers are used largely for radio-frequency transmitters where the output is tuned to the fundamental and presents such a low impedance to the harmonic frequencies that they are not permitted to develop any power in the antenna system.

Push-pull Amplifiers.—To get more power out of an amplifier, it is possible to put two or more tubes in parallel, connecting the grids together and the plates together. Then the plate resistance will be half that of a single tube and with

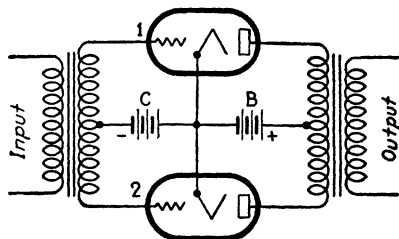Fig. 18.—Push-pull amplifier.

a given excitation on the grid the power output will be doubled.

Tubes may also be connected in what is known as *push-pull*, shown in Fig. 18. Here the tubes are operated so that the input signal drives one grid (tube 1) less negative at the same time it drives the other (tube 2) more negative. In tube 1, therefore, the plate current will increase and in the other tube the current will decrease. This amounts to an output current flowing through the two windings of the output transformer in series but any second harmonics generated flow down through the top and up through the lower output transformer winding so that these second and other even harmonic currents produce no effect on the output winding of the transformer and hence do not appear in the loud-speaker or other load. Such circuits are almost invariably used in modern radio receivers. They require much less filtering of the 60-cycle power, deliver more power than a single tube by a factor of about 3, and the second harmonics are much lower.

If the voltage available to drive a single tube (*i.e.*, that across the secondary of the input transformer) is 100 volts, twice this voltage will be necessary to drive the two push-pull tubes,

i.e., 100 between each cathode and grid. Therefore the turns ratio of the transformer must be doubled.

Amplifiers for Industrial Uses.—In uses other than communication little is cared about distortionless amplification. In many cases the greatest *change* in plate current with a given grid-voltage excitation is desired. It is the magnitude of the *change* that is important, not the magnitude of the current. For example, a given relay may close on 6 ma. and open on 1 ma. A relay can be built which will work on a differential of much less than this, say close on 2 ma. and open on 1 ma. but it is more expensive.

Therefore most industrial amplifiers are biased so that the plate current without excitation is small and large when the grid is excited. This amounts to class B amplification.

Amplifier Tubes in the Measuring Laboratory.—The amplifier tube has extended the range of many measuring instruments whether they are mechanical, chemical, or electrical. In so doing the electron tube has contributed enormously to man's knowledge of the ultimate constitution of matter. This knowledge has increased very rapidly when new measuring instruments and new experimental processes have been invented. When, however, the measurements have advanced into the region where the instrument disturbs the object or condition to be measured, it has reached the limit of its usefulness. Then, either a new instrument is needed, or the old one must be further refined.

Thus the vacuum-tube voltmeter has made possible the measurement of voltages in circuits where any other form of instrument would so disturb the conditions that they would no longer be normal. The amplifier has extended the range of voltmeters, ammeters and wattmeters; it has made them more sensitive and more accurate. In many cases the amplifier has eliminated the source of error inherent in the human link of the measuring chain.

Quoting Dr. Hull,[1]

Electronic devices enable us to measure without disturbing them *smaller voltages, smaller currents, smaller distances, smaller times, smaller*

[1] HULL, A. W., Electronic Devices as Aids to Research, *Phys.*, June, 1912; see FLEMING, AMBROSE, Thermionic Valve in Scientific Research, *J. Franklin Inst.*, August, 1935.

sounds, and smaller light. Examples of smaller voltages include the transient voltages due to heartbeat and nerve reaction; of small currents, the ionization due to a single ion or photon; of small distance, the separation of atoms in a molecule; of small time, the breakdown of a spark gap in air or vacuum, which can be timed to $\frac{1}{100}$ microsecond by the cathode-ray oscillograph; of small sounds, speech transients and the noise of machines; of small light, the radiation from a distant star.

The amplifier not only extends the range of voltmeter and current meters but it facilitates the adjustment of Wheatstone bridges of the various types not only in making it possible to use frequéncies to which the ear is not sensitive, *i.e.*, very low or very high frequencies, but to measure accurately values of electrical quantities at bridge-tone levels too weak for the ear to perceive the point of balance. Often the ear is dispensed with entirely in favor of a visual indicating instrument operated by a vacuum-tube amplifier whose input is the voltage appearing across the balance points of the bridge.

Thus the human error due to characteristics, or fatigue, of the ear are avoided in favor of an untiring electronic instrument.

Measurements of very low currents produced in an ionization chamber by means of an amplifier were described by R. D. Bennett in the *Journal of Scientific Instruments*, August, 1930. In this case the grid terminal cap of a screen-grid tube was placed in the chamber and properly shielded.

Direct-current Amplifiers.—In many cases the voltage to be amplified is a mere pulse, a very low frequency a.c. or a d.c. voltage or current. In these cases coupling one tube to another by means of a transformer or a resistance and condenser will not work. The pulse, or the current or voltage, will not build up a voltage across the coupling transformer to affect the grid of the following tube.

A circuit used in case that very slow variations in voltage or current are to be amplified is shown in Fig. 19. The second grid must be maintained negative with respect to the cathode of the tube by means of a separate C battery. Since the coupling between the two tubes is very close, trouble is had with instability unless the separate stages are carefully shielded. It is often necessary to use separate A batteries.

Introduction of tubes whose cathodes are heated by an insulated filament (heater-type tubes) simplified tremendously

the problem of d.c. amplification, often called direct-coupled amplifiers. In Fig. 20 is a Loftin-White amplifier. In Fig. 21 the cathodes may have different voltages with respect to all the

FIG. 19.--Direct-current amplifier.

FIG. 20.—Direct-coupled amplifier.

FIG. 21.—Operation of typical direct-coupled amplifier.

other elements in the circuit while the filaments which heat the cathodes may be operated from the same source. All positive and negative voltages may be taken from a single source across which is a voltage divider. All that is necessary to make a

grid negative with respect to its cathode is to connect that grid to a point of lower potential than the cathode.

With the use of high-mu tubes, usually of the screen-grid type, very high amplifications may be secured. In the circuit of Fig. 21 the process of amplification is as follows: Suppose the first tube to have a mutual conductance of 1,000 micromhos, with the load in the circuit. This means a tube whose plate resistance is high compared to the load resistance. Suppose it to be coupled to the second tube through 100,000 ohms, the second tube having a mutual conductance of 1,000 and a low plate resistance and worked into a low-resistance meter.

Along the voltage divider appear various voltages used to bias the grid of the second tube and to furnish plate voltages for both tubes. The first tube has its anode 250 volts positive with respect to its cathode. Suppose that 1 ma. flows through the first tube and the coupling resistor. This produces a d.c. drop along this resistor of 100 volts.

Now if the cathode of the second tube were connected at point *C* on the divider, the grid of this tube would be 100 volts negative with respect to its cathode because of the 100-volt drop along the coupling resistor due to the plate current taken by the first tube. This is too much bias for the second tube. Therefore the cathode of this tube must be made more negative (which will make the grid *more positive* or *less negative*), and this can be done by moving the cathode connection to a point such as *D* on the divider. Now if there is a 90-volt drop along the divider between *C* and *D*, the cathode will be actually only 10 volts positive with respect to the grid. This amounts to a −10-volt bias on the second tube grid.

Suppose under these conditions 5 ma. flows in the plate circuit of the second tube. The problem is to change the current flowing through the 1,000-ohm resistor in the input to the first tube and to see what happens in the output of the second tube.

Suppose this input current increases so that the first tube grid is now more negative than it was before, say by 0.1 volt. It is now 1.1 volts negative and the change in plate current will be 0.1 volt $\times 10^{-3}$ mho or by 0.1 ma. This plate current will *decrease* because the grid of the tube is more negative. The new plate current value will then be 0.9 ma. and the voltage drop along the plate resistor will be 90 volts, which will make

the grid of the second tube the same voltage as the cathode of that tube since the grid is 90 volts negative with respect to point C and the cathode is 90 volts negative with respect to the same point.

If the mutual conductance of the second tube is 1,000 micromhos, each volt change in grid bias will produce about 1-ma. change in plate current. Since the grid is now less negative than it was, the plate current will *increase* and the resultant plate current will be 15 ma. instead of 5 ma. (5 + 10 ma.).

Thus a change of 0.1 ma. in the input to the first tube has become a change of 10 ma. in the output of the second tube, a current amplification of 100 times.

It is possible to make an increase in current in the input circuit produce a decrease in the output current if desired by reversing the proper connections. Several stages may be operated in this manner, but since all the tubes are connected together through the voltage divider, there is always great danger from regeneration and instability. Vacuum-tube amplifiers are not well adapted to current amplification or to amplification of voltages secured from low-resistance sources. Thus it is difficult to amplify the current output from a thermocouple or photovoltaic cell.

When a low current, or a current which cannot be made to pass through a high resistance must be amplified, it is better to use a phototube as an amplifier. Thus a small current can be made to deflect a sensitive galvanometer. The mirror on this instrument may reflect a beam of light, which has no weight and therefore requires no power to move, into a photo-electric tube (see, however, the high-gain amplifiers to follow).

A High-gain Direct-current Amplifier.—An amplifier[1] making use of the high amplification factor of screen-grid tubes is shown in Fig. 22. This arrangement uses the high internal resistance of one tube as the load resistance of another tube, and therefore is a form of direct-coupled amplifier. The characteristics are shown in Fig. 23. Since the two tubes in series divide the battery voltage, when the voltage across one tube decreases, that across the second tube increases. These increases are created by varying the input to the first tube, *i.e.*, by applying the voltage to be amplified.

[1] MEISSNER, E. R., *Electronics*, July, 1933.

The voltage amplification of the two tubes amounts to over 600 times, or nearly one-half the amplification factor of one of the tubes. To gain this amplification by conventional resistance
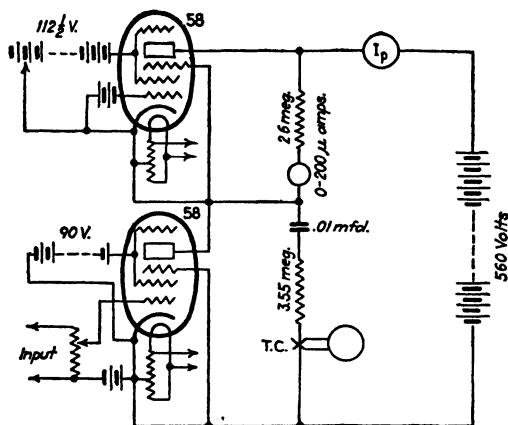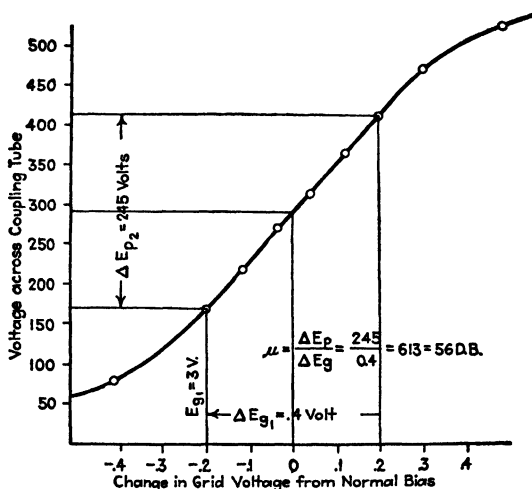

FIG. 22.—High-gain amplifier of direct-coupled type.

FIG. 23.—Characteristics of amplifier shown in Fig. 22.

coupling would require a plate-battery voltage of over **6,000** volts to take care of the loss in voltage across the coupling resistor, an obviously impracticable set-up.

This amplifier can be used for alternating current and with a coupling resistor of 3.55 megohms a voltage gain of 613 is secured

which is sensibly flat from well below 30 cycles to 10,000 cycles.

Another high-gain amplifier realizing still more of the amplification factor of the tube has been described.[1] This set-up uses type-57 tubes which have amplification factors of the order of 1,500. The designer points out that the difficulty in such circuits is to provide a coupling or load resistance which has a comparatively low d.c. value but a comparatively high a.c. value. The lower the d.c. resistance, the lower may be the total B voltage required; the higher the a.c. resistance, the
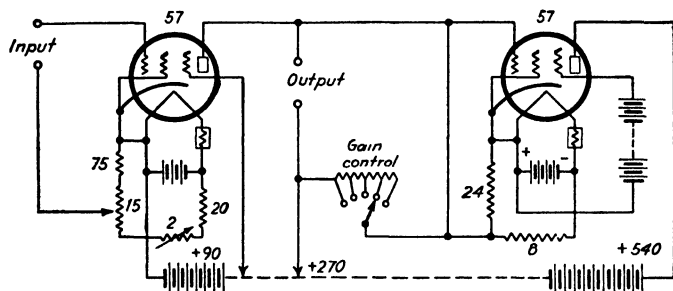
Fig. 24.—Circuit producing exceptionally high amplification—2,500 for two tubes.

greater the proportion of the mu factor of the tube that is realized in actual amplification.

Schmitt uses a second 57 as a practically infinite resistance load for the first. He notes that the plate current of such a tube rises at first quickly up to about 75 volts on the plate and then rises slowly and linearly as far as 600 to 700 volts. Thus at 200 volts the static resistance (E_p/I_p) is about 100,000 ohms while the a.c. resistance at this point is of the order of 10 megohms.

The circuit in Fig. 24 permits a voltage amplification of 2,500 (with tubes of this mu factor) with plate-supply voltages of the order of 300 to 600 and develops output voltages of the order of 450 with negligible distortion. Separate batteries are necessary; but the set-up is very stable.

The Wold-Wynn-Williams Amplifier.—P. I. Wold patented an amplifier of the bridge type in 1916 (1,232,879) which was

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[1] SCHMITT, OTTO H. A., A Method of Realizing the Full Amplification Factor of High-mu Tubes, *Rev. Sci. Instruments*, December, 1933.

later improved by Wynn-Williams.[1] More recently J. M. Eglin[2] described modifications of the circuit. It will be seen below that the modern tubes of the FP-54 type have been employed in this circuit to measure very low currents, approaching a few electrons per second.

The Wynn-Williams circuit appears in Fig. 25. It is a bridge with two resistance arms and two arms made up of vacuum tubes. In operation the bridge is balanced; then the input is used to unbalance one of the grid-cathode circuits with the result that an amplified current is read by the meter.

In this circuit the grid-cathode leakage resistance of the tube becomes part of the input; Eglin made this portion of the circuit fixed and known in value by means of a grid bias from a battery acting through a grid resistance. Here a small current to be measured is forced to flow through a high resistance in
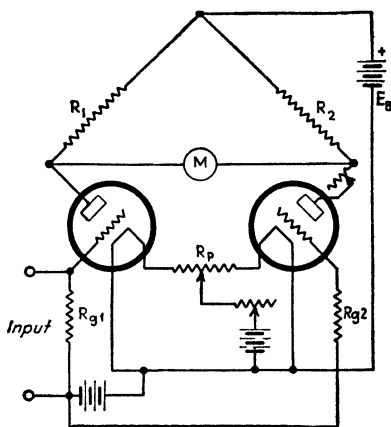
FIG 25 - Bridge-type of tube amplifier.

the grid circuit of one of the tubes; this changes the plate current of that tube which is larger than the unknown current. The bridge really is a high-resistance ammeter.

The tubes in this circuit must have low leakage compared to the values of conductance used in the grid circuit. With resistance between grid and cathode of the order of 10,000 megohms a current amplification of 900,000 times is obtained and a current as low as 10^{-14} amp. can be measured.

The difficulties with the system are inherent in the variability of the amplifying properties of the tubes themselves, with variations of the battery voltages, and of the difficulty in securing sufficient shielding. Some of these variables may be balanced out by more complicated circuits. Many of the troubles seem

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[1] *Proc. Camb. Phil. Soc.*, vol. 23, p. 810, 1927; *Phil. Mag.*, vol. 6, p. 324, 1928.

[2] EGLIN, J. M., Direct-current Amplifier for Measuring Small Currents, *J. Optical Soc. Am.*, vol. 18, pp. 393–402, May, 1929.

to have been lessened by the introduction of tubes especially made for this purpose (so-called electrometer tubes).

An A.C.-operated D.C. Amplifier.[1]—The use of an a.c. supply voltage for the plates of a d.c. amplifier has a definite advantage over conventional d.c. amplifier circuits in that it eliminates the necessity of cascading "B" supply voltages or of using bucking batteries between stages.

With reference to the d.c. amplifier used in Fig. 26 to indicate the d.c. potential accumulated across C_1 by the phototubes, the
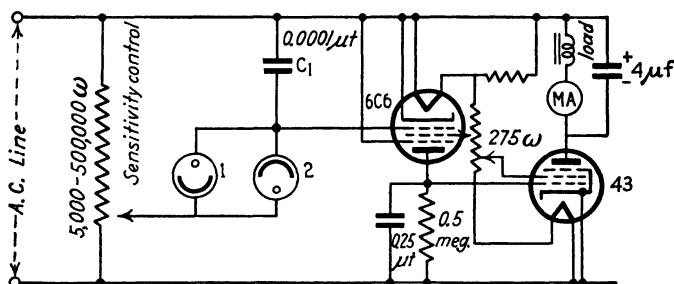
FIG. 26.—An a.c.-operated d.c. amplifier.

plate supply is the a.c. line. The tubes in this circuit can conduct only during the part of the a.c. cycle that their own anodes are positive with respect to their own cathodes. Because of the direction of current flow through the tubes, the drops in the load resistors are such that the plates of the tubes assume potentials negative with respect to the plate supply. The plates of the tube in these circuits assume average potentials which are actually negative with respect to their own cathodes. The tube current, and hence the drop across the plate load, is controlled as in conventional circuits by the grid bias. The plate of the first amplifier stage can be connected directly to the grid of the second stage to supply d.c. bias and signal to the output stage. The output will be a rectified pulsating d.c. current which is smoothed out by the indicated electrolytic condenser and passed through the output load.

A Sensitive Relaxation-type Current Amplifier.[2]—The circuit in Fig. 27 can be used to amplify the extremely small currents

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[1] SHEPARD, F. H., JR., Miscellaneous Applications of Vacuum Tubes, *Proc. Radio Club Am.*, June, 1935.

[2] SHEPARD, loc. cit.

of a phototube which is receiving very small amounts of light. The circuit consists primarily of a phototube, a relaxation oscillator the frequency of relaxation of which is controlled by the light or current through the phototube, a diode rectifier connected to the relaxation oscillator in such a way that the voltage it develops indicates the frequency of relaxation, and a power-output tube controlled by the diode-output voltage. The operation of the circuit is as follows: The oscillator circuit oscillates violently, builds up a negative charge on its grid, and suddenly blocks or stops oscillating. The oscillator will not again start oscillating until the charge on C_1 has leaked off through the phototube to such an extent that the oscillator will again
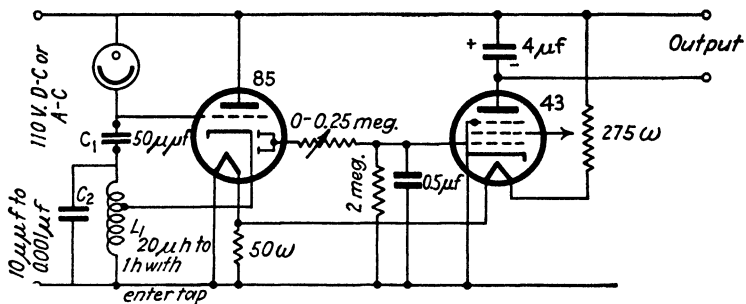
Fig. 27.—Relaxation-type current amplifier.

conduct. Thus the time between the bursts of the oscillations of this oscillator are directly controlled by the rate at which C_1 is discharged through the phototube.

There is a direct linear relation between frequency of relaxation and light on the phototube. Current as low as 0.001 μa. will operate a 20-ma. relay and even lower currents will operate it if the apparatus is placed in a desiccator.

Development of the FP-54.—Several sources of leakage, and other currents that masked the effect upon the tube of the current to be measured, limited the lower values of current which could be measured with conventional tubes. The leakage from grid to cathode, ionization of residual gas within the envelope, and other sources of undesired currents were investigated.

Insulation leakage is reduced to the lowest limit by the use of quartz. Dr. L. P. Smith showed that a large residual source of leakage in a vacuum tube was positive ion emission from the hot

cathode which amounted to 10^{-11} amp. for a well-aged tungsten filament at 2100°. Dr. DuBridge found that photo-electric emission from the grid due to the light from the filament amounted to 10^{-12} amp. when a pure tungsten filament was used and of the order of 10^{-15} amp. from a thoriated filament at about 1700°K.

The lower current from the thoriated filament is to be expected since a pure tungsten cathode must be heated to a considerably higher temperature than the thoriated tungsten with consequent greater radiation of light. Another source of leakage was that due to soft x-rays produced by electrons impacting on the space-charge grid and anode.

As a result of these investigations carried out in the General Electric Research Laboratories a special tube was designed (FP-54) with which it has been possible to measure currents as low as about 60 electrons per second.

The FP-54 is a two-grid tube; one grid is maintained at 3 volts positive to hold back the positive ions emitted from the filament; its thoriated filament operates at a temperature of 1700°K., its plate current is 40 μa. "This microtube has the distinction of being entirely impractical. Its applications, present and future, as far as the author can see, are purely scientific. It counts cosmic rays. It measures, in cooperation with the photo-electric cell, the light from distant stars, being able at present to detect the light from a star of the 14th magnitude. It records the fragments—neutrons, protons, and alpha particles—of atomic nuclei smashed by high-speed ions. The structure of these atomic nuclei, the 92 hitherto invisible elements of atoms, appears to be the next objective of scientific research, the next nature fortress which science aspires to storm.[1]"

Fig. 28.—The FP-54 tube.

[1] HULL, DR. A. W., *Am. Inst. Mining Met. Eng.*, Buffalo, Oct. 6. 1932.

The ratings and data for the FP-54 are summarized as follows:

Filament voltage................ 2.5 volts
Filament current............. .. 0.110 amp.
Space-charge grid voltage....... . +4 volts
Control-grid voltage.. .... −4 volts
Plate voltage..... .. .. +6 volts
Input resistance   .. .. 10^{16} ohms (approx.)
Control-grid current   .... 10^{-15} amp. (approx.)
Plate current   .... 40 microamperes
Mutual conductance   .. 25 microamperes per volt
Plate resistance..   . . 40,000 ohms
Amplification factor   1
Maximum over-all dimensions:
    Length   .... $6\frac{1}{4}$ in.
    Diameter.   .... $1\frac{9}{16}$ in.

From the standpoint of one familiar with conventional tubes, this amplifier is a distinct departure. The structure is beautifully mounted on quartz so arranged that the assembler's hands cannot touch the support between grid and cathode during the assembly.

It has a very high grid resistance—of the order of 10^{16} ohms compared to the 10^8 or 10^9 of most tubes. This high resistance is essential to the measurement of very small currents. It operates at a plate potential of only 6 volts thus making it possible to use very large storage batteries for plate, filament, and grid-bias supply reducing fluctuations in the battery voltage with their incidental difficulties. The characteristics of the tube are shown in Fig. 29.

Application of the FP-54.—This tube is a current amplifier; if voltage amplification is desired either another tube must be. used, or the FP-54 used merely as a coupling tube between the circuit under measurement and the amplifier tube. Used with an input resistance of 10^{10} ohms, a current amplification of 250,000 may be obtained. Used as an electrometer with a galvanometer of a sensitivity of 10^{-10} amp. per millimeter connected in the plate circuit, a sensitivity of 250,000 mm. per volt may be obtained.

The tube may be used in any of the usual circuits designed for d.c. amplification. Several of such circuits and a discussion of their merits will be found in the *Journal of the Franklin Institute*, page 209, March 1930, W. B. Nottingham. These are circuits for triodes, but all that is necessary to adapt this

tube with its two grids to these circuits is to provide the proper voltage tap on the battery for the space-charge grid.
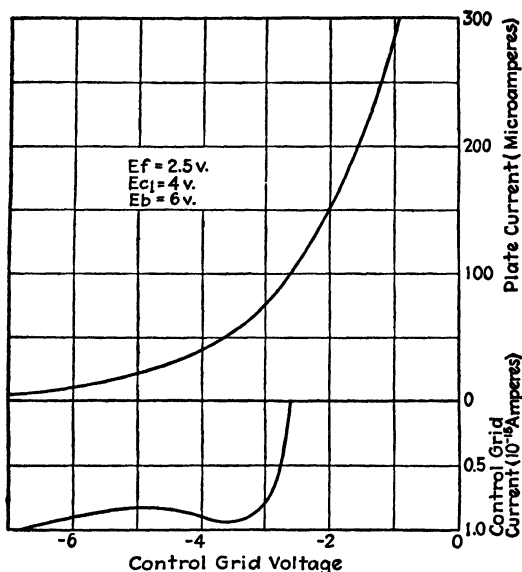

$Ef = 2.5$ v.
$Ec_1 = 4$ v.
$Eb = 6$ v.

FIG. 29.—FP-54 characteristics showing low grid currents.

$R_1 = 1,000$ Ohms $R_3 = 17$ Ohms $R_S = 10,000$ Ohms $V = 0$-200 MV
$R_2 = 400$ Ohms $R_4 = 400$ Ohms $S = 10,000$ Ohms $R_6 = 10^7$ to 10^{12} Ohms
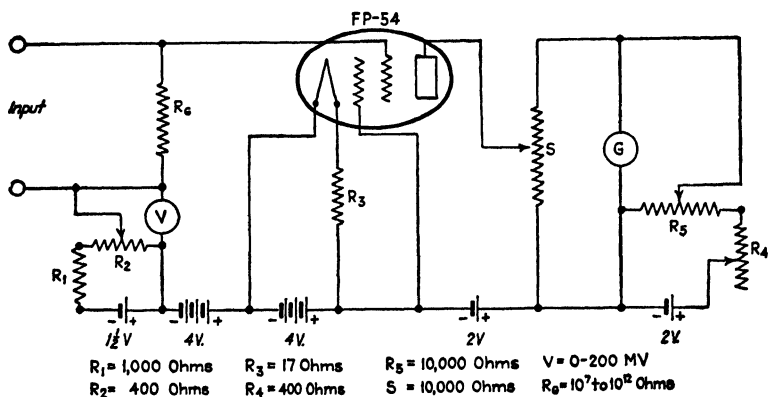
FIG. 30.—Single-tube circuit for measuring currents as low as 10^{-14} amp.

The circuit shown in Fig. 30 is recommended for the measurements of current as small as 10^{-14} amp. It requires only a 12-volt storage battery and a 1.5-volt dry cell.

The method of operation is as follows: With the filament voltage set at its rated value (2.5 volts) and V reading zero, the

galvanometer is made to read zero by adjusting R_4 and R_5. The input current i will then produce a change in grid potential e equal to $R_g i$ and the change in plate current will cause a deflection of the galvanometer. By adjusting R_2 the galvanometer is brought back to zero. The meter V then reads the value of e, from which i is computed if R_g is known. The *sensitivity* of the amplifier depends upon the value of R_g and on the sensitivity of the galvanometer. Thus, if G_m is the mutual conductance of the tube

$$G_m = \frac{di_p}{de_g} = \frac{i_g}{R_g i} = \frac{kd}{R_g i}$$

where k is the galvanometer sensitivity, i_g the galvanometer current, and d the galvanometer deflection for the input current i.

For the FP-54, G_m is equal to about 20 μa per volt. Hence, for example, if $k = 10^{-9}$ per millimeter, $R_g = 10^{10}$ ohms, then d will be 1 mm. for $i = 4 \times 10^{-15}$ amp. The current amplification factor is

$$A = \frac{i_g}{i} = R_g G m,$$

and hence in this example $A = 20 \times 10^4$.

Two-tube Balanced Circuit.—For currents smaller than 10^{-14} amp., or in circuits where great stability and precision are desired, the circuit shown in Fig. 31 is recommended. The circuit is "balanced" by adjusting the plate-cathode and the 10,000-ohm resistors so that variations in plate-supply voltage cause no change in the galvanometer. The effect of the plate resistors is to make the change in current with plate-supply voltage in the two circuits equal. An adjustment of the 10-ohm unit makes the galvanometer reading independent of filament voltage. The circuit is then extremely stable and a galvanometer with a sensitivity of 10^{-10} amp. per millimeter may be used, together with a grid resistance of 10^{11} ohms. The ideal sensitivity then will be about 5×10^{-17} amp. per millimeter, though on account of the bridge arrangement the real sensitivity will be half as great, or 10×10^{-17} amp. per millimeter. The actual amplification factor will be about 10^6.

For measuring resistance of order of 10^{12} ohms the circuit of Fig. 31 is useful. High voltages are not necessary. The grid resistance should be of the same order of magnitude as the

unknown which is bridged across the input terminals of Fig. 31. Here $R_x = (E/I) - R_g$, where E is the reading of the milli-voltmeter V and I is obtained from the calibration curve of the instrument and the galvanometer used in the tube circuit;
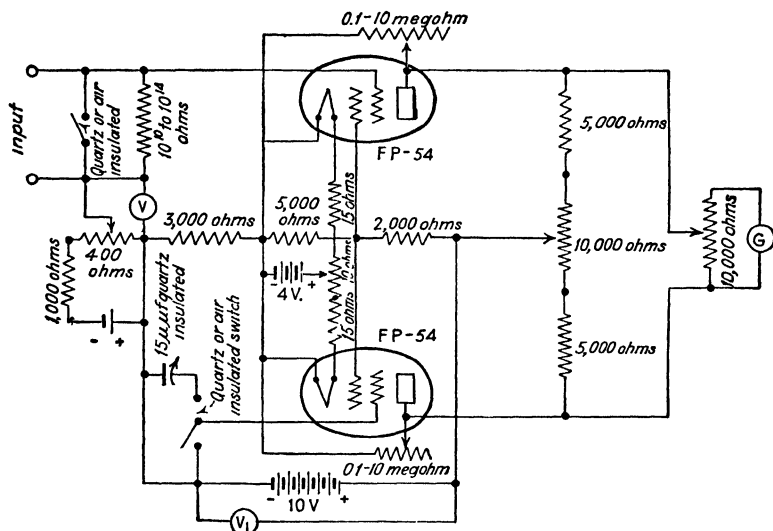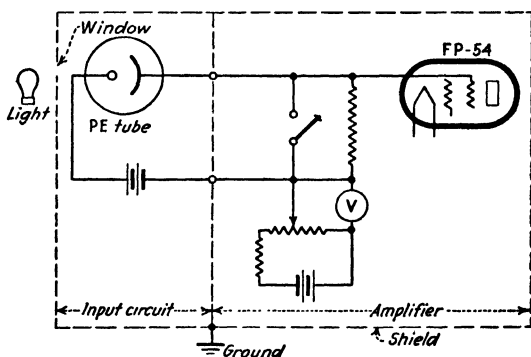

Fig. 31.—Balanced circuit for low-grid-current tube.

Fig. 32.—Circuit for measuring phototube currents.

R_x is the unknown and R_g the grid resistance.   This galvanometer can be of the portable telescopic type having a sensitivity of 10^{-8} amp. per millimeter and a resistance of about 7,000 ohms. The circuit may be used for measuring photocell current as shown in Fig. 32.

In operation[1] the procedure is as follows: The battery-supply voltage is checked by the voltmeter V_1 and the external galvanometer made to read zero by balancing the circuit with zero input. The amplifier is calibrated (with input circuit open) by adjusting the potentiometer through its range, reading the voltage shown by the calibrating millivoltmeter and plotting the current through the grid resistor against the external galvanometer reading.

The current is found from $I = E/R_g$, where I is the current through the resistor, E is the calibrating meter reading, and R_g is the known grid resistance.

A calibration should be made or checked each time the amplifier is used. Then the calibrating voltage is removed and the unknown current from the external circuit. For example, the photocell shown in Fig. 32 is connected to the amplifier and the galvanometer reading noted. The value of current is then read from the calibration curve. When the proper precautions as to shielding, dryness, etc., are taken, this method is very satisfactory.

If it is desired to avoid the necessity of referring to a previously made calibration, a null method may be used. The galvanometer is made to read zero with zero calibrating potential, the input circuit is connected, and the galvanometer indicator swings up scale. It is then brought back to zero by adjusting the calibrating potential. This value is read from the calibrating meter and the current calculated as before. If the resistance of the input circuit is much lower than that of the grid resistor, this null method is not satisfactory.

A still greater sensitivity may be obtained by "floating" the two control grids, *i.e.*, by removing the grid resistance and switching the lower switch to the capacitor. The potential of each grid will then slowly decrease at the same rate by adjustment of the variable 15-$\mu\mu$f capacitor. The input current i will now cause the potential of tube 1 to decrease faster and this will produce a steady drift of the galvanometer, which may be timed by a stop watch.

The current is then determined from

$$\frac{diG}{dt} = G_m \frac{deg}{dt} = G_m \frac{i}{C}$$

[1] MOLES, F. J., *Gen. Elec. Rev.*, March, 1933.

where C is the grid capacitance (about 6 $\mu\mu f$) and G_m is 20$\mu a/v$. For a galvanometer sensitivity of 10^{-10} amp. per millimeter, a drift of 1 mm. per second means an input current of

$$\frac{10^{-10} \times 6 \times 10^{-12}}{20 \times 10^{-6}} = 3.4 \times 10^{-17} \text{ amp.}$$

This amplifier may thus be used in various ways to measure direct currents down to 10^{-17} amp. and resistances up to 10^{12} ohms. Under the best conditions, the precision of the measurements is probably better than 5 per cent. However, the accuracy of the measurements depends on the known value of R_g, the shielding which the user provides for the external circuits, the care in observing the following precautions, and similar factors.

1. The circuit in which the current is to be measured and the batteries must be enclosed in a shielded case similar to that used for the amplifier itself.

2. The tube control grid and control-grid circuit must be insulated with fused quartz or amber, and kept dry. They may be kept dry by operating them at higher temperature than the surroundings, or by the use of a dehydrating agent such as calcium chloride or phosphorus pentoxide. In one case a lighted incandescent lamp kept the instrument free from moisture condensation when not in use.

3. The connections should be absolutely firm and tight.

4. The batteries should be kept in first-class condition.

5. Only the best insulation should be used in the control-grid circuit, such as quartz or amber.

6. Rheostat slides should make firm positive contact. Cleaning with sandpaper is advised.

7. The switches used in the circuit of Fig. 31 should be of small capacity and without contact potentials.

8. The output current is a *linear* function of input voltage only over a limited range. The amplifier must be calibrated if a direct deflection rather than a null method is to be used.

Uses other than those mentioned are the measurement of phototube currents in astronomical determinations of starlight, the measurement of radium and x-ray emanations, etc.

Measurements of unknown resistance by the method described above depend upon the known values of the grid resistance R_g.

Several values of R_g will make possible a considerable range of resistance measurement. These standards should exhibit but

little change with age, temperature, and moisture and should be as small as possible physically.

In actual practice such a circuit has been found capable of detecting currents of 5×10^{-18} amp. (about 30 electrons per second).

Two-stage Amplifier.—For cases in which it is desired to measure currents of 10^{-9} to 10^{-14} amp. with a very rugged galvanometer or microammeter, the circuit of Fig. 33 has been found useful. The first stage is a bridge circuit similar to Fig. 31, but with the second tube replaced by a resistance of 100,000 ohms. This stage may be balanced by adjustment of the 10,000-ohm resistor. In the second stage a tube of high mutual conductance is used. A bridge circuit may be used in this stage also, though a smaller drain on the B batteries is obtained with the simpler arrangement shown. The second stage is balanced by adjustment of the 400-ohm resistor.

With a microammeter of given range the sensitivity of the amplifier may be changed by changing the input grid resistance. The sensitivity of the whole arrangement as shown is approximately given by

$$\frac{i_A}{i} = \frac{1}{2} \times \frac{\mu_1 R_4}{r_p + R_4} \times G_{m2} R_g,$$

where i_A = microammeter current.

i = input current.

r_p = internal plate resistance of first tube.

μ_1 = voltage amplification factor of first tube.

G_{m2} = mutual conductance of second tube.

For the FP-54, $\mu = 0.9$ and $r_p = 45,000$ ohms, and for the second tube, G_{m2} may equal 1,500 μa per volt. Hence if $R_g = 10^{11}$ ohms, an output current, i_A, of 1 μa will be obtained for

$$i = 4 \times 10^{-14} \text{ amp.}$$

and the current amplification will be 2.5×10^7.

It has been found that i_A is a linear function of i for input voltages $(= R_g i)$ less than about 0.5 volt. For larger input voltages, up to 5 volts, a null method should be used to prevent the FP-54 grid voltage from becoming low enough to draw a high grid current.

Metallic grid-leak resistors may now be obtained up to 100 megohms and composition resistors up to 10^{14} ohms. Resistances up to a thousand megohms may be made by ruling India-ink marks on drawing paper or hard rubber or amber, and inclosing in a drying tube. Still higher resistances may be made by evaporating or sputtering thin metal films on to a glass or quartz rod, keeping the rod in paraffin or in vacuum. Resistances made by the International Resistance Company, Philadelphia, and the S.S. White Dental Company, New York, are regularly used.
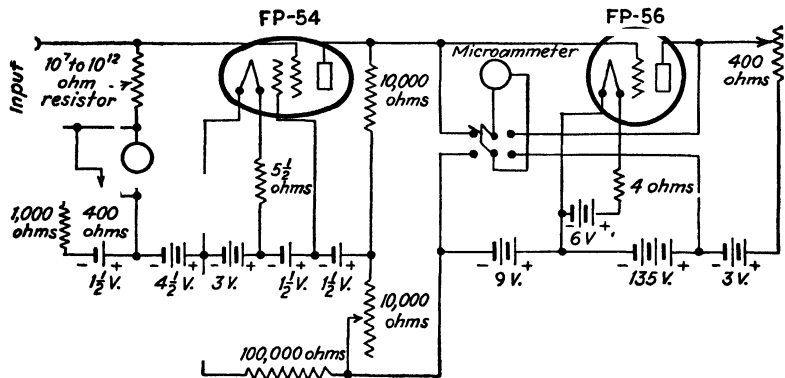
Fig. 33.—Two-stage amplifier measuring currents of 10^{-9} to 10^{-14} amp. with rugged galvanometer.

Stabilized One-tube Circuit.—To obtain the greatest sensitivity using one tube and for making measurements over a long period of time the circuit shown in Fig. 34 is recommended. This circuit can be adjusted so that changes in battery voltage as well as drift in plate current have no effect on the balance of the galvanometer. This circuit is adjusted by setting the filament current I to obtain approximately the rated filament potential and bringing the galvanometer to zero by varying the 50- and the 10,000-ohm resistors in the plate circuit. Then by varying the filament rheostat a point should be found where the rate of change of galvanometer deflection with filament current is zero. If this point cannot be found within a range of plus or minus 3 or 4 per cent of filament current, change the setting of the 50-ohm potentiometer next to the filament meter and repeat. Then balance the galvanometer to zero with the plate resistors. After operating 20 or 30 min. it may be necessary to readjust the plate resistors for zero balance.

With the rate-of-drift method (floating grids) the passage of 30 electrons per second can be detected and measured, and the unevenness in their flow makes itself felt. If tubes can be constructed having a ten thousand times smaller grid current—and this is not impossible—the individual electrons might be indicated by the electronic tube.

When the input terminals of an FP-54 followed by a 112-A tube are connected to a caesium phototube illuminated by a small
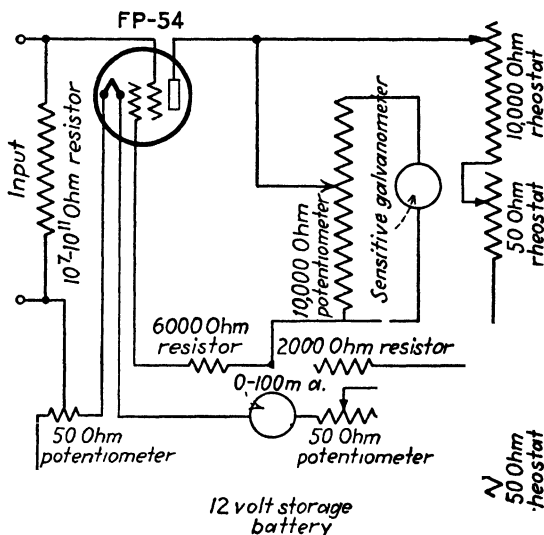

Fig. 34.—Stabilized one-tube circuit for FP-54.

headlight lamp, an output of several microamperes is observed when the lamp filament is at a temperature such that it is scarcely visible to the eye in a dimly lighted room.

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DuBRIDGE, L. A., and HART BROWN, Improved D. C. Amplifier, *Rev. Sci. Instruments*, October, 1933. A method of balancing out effects of variations of filament emission is given.

MULLER, R. H., and G. E. SCHRIVER, Precision Radiation Integrater, *Rev. Sci. Instruments*, April, 1935. This is a condenser charging method using a FP-54 which drives an amplifier which operates electromagnetic counter.

VAN VOORHIS, S. N., and G. P. HARNWELL, A Balanced Electrometer Tube and Amplifying Circuit for Small Direct Currents, *Rev. Sci. Instruments*, July, 1934.

MORTON, C., Portable Thermionic Electrometer, *J. Sci. Instruments*, September, 1932.

Author uses General Electric "electrometer tube" (FP-54). The device has a sensitivity of 0.06 ma. per volt; 0.1 mv. through 10^{10} ohms can be detected. The author cites the use of the amplifier for measuring glass-electrode potentials.

MACDONALD, P. A., and J. T. MACPHERSON, D. C. Amplifiers Using FP-54, etc., *Phil. Mag.* and *J. Sci.*, vol. 15, pp. 72–81, 1933.

TAYLOR, A. H., and G. P. KERR, *Rev. Sci. Instruments*, vol. 4, pp. 28–32, 1933.

Low-noise Amplifier Tube.—Measurements of very low voltages, especially at low frequencies, are made difficult by noises originating in the input circuit to the first tube of the amplifier or within the first tube itself. Thus, any momentary changes in the emission may cause minute changes in plate current which, occurring at an audio rate or at a frequency comparable to that under measurement, will be amplified by the succeeding amplifiers and limit the lower order of voltages that can be measured. Gassy tubes are great sources of trouble. Kingdon[1] has stated that a single positive ion may oscillate as many as twenty-five times about the grid before it finally strikes it. In this blundering-about it may neutralize as many as 600 electrons, producing considerable changes in the space charge and consequently in the plate current.

By producing a tube with a very high vacuum and taking other precautions in its manufacture, tube makers have produced amplifying tubes especially for use where considerable amplification takes place. Among them is the PJ-11 (General Electric Company) developed by Metcalf and Dickinson. The PJ-11 produced a noise output of 5 to 10 μv, compared to the 222 (a screen-grid tube used in battery-operated radio receivers) which produced 52 μv. Others produced considerably more noise voltage. The PJ-11 measures voltages 10 times smaller than could be detected before—down to 0.1 μv. Its uses are

[1] KINGDON, K. H., *Phys. Rev.*, vol. 21, p. 408, 1923.

yet to be discovered. It may find its greatest application in physiology and measuring of heartbeat voltages, nerve impulses, even thought waves.

The 38-type tube compared to the PJ-11 from the standpoint of inherent noise is described by E. A. Johnson and C. Neitzert, *Rev. Sci. Instruments,* May, 1934, p. 196. It seems to be less microphonic, and operated at low voltages it has a very high input resistance and is economical to operate. Four stages give a voltage amplification of about 4×10^5 at 1,000 cycles per second. The amplifier, terminated with a Raytheon LA tube, feeding a thermo-meter through a transformer gives about 10 milliamperes output with a R.M.S. input of 0.5 volt. The authors describe the use of two new circuits to limit the input noise, finding it possible to measure 10^{-8} volt at 400 cycles and to detect 10^{-9}.

PJ-11 RATINGS AND DATA

Filament:
  Voltage............... 5 volts
  Current. 0 25
  Type: Thoriated tungsten

Average characteristic values at:
  E_B = 135 volts
  E_C = 1.35 volts
  Plate current...... 0.45 ma.
Amplification factor.. 30
Plate resistance...... 100,000 ohms
Mutual conductance. 0.3 ma. per
                        volt

Conditions for resistance—coupled amplification:
Supply voltage
  (max.).......... 180 volts
  Grid bias.......... −1 5 volts
  Load resistance.... 100,000 ohms
  D.c. plate current.. 0.45 ma.
  Voltage amplification........... 15
  R.M.S. noise voltage (expressed as equivalent voltage applied to the grid and integrated over a 200-cycle frequency band).... 0.5 μv.

Electrometer Tubes.—The Westinghouse Company builds two semi-electrometer tubes, the DRH-506 and DRH-507, the first with a low energy filament for operation from a storage battery. These tubes are operated at very low anode voltage (about 6 volts). Their mutual conductance at rated operating conditions are 60 and 90 micromhos respectively. The control grid current is less than 10^{-12} amp. at the rated operating point in both tubes. They are of the inverted triode type; that is, the plate is used for control. The anode in the form of a grid between the filament and grid is effective in reducing positive ion flow from the filament to the grid. This type of control makes

possible nearly a linear relation between control voltage and anode current.

The control electrode in the form of a plate outside the grid-shaped anode is mounted on a fused quartz rod. Placing the anode between the control electrode and the cathode reduces positive ion current and improves the performance at low anode potentials.

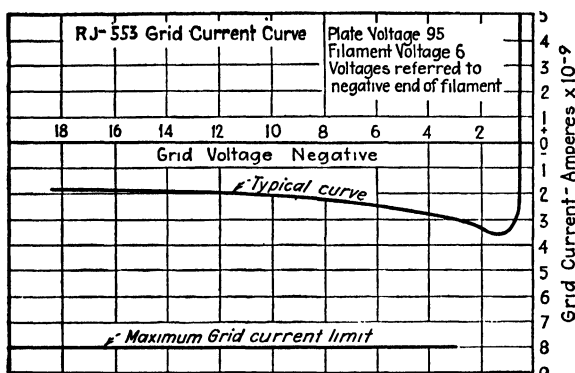Westinghouse engineers have met a demand for a series of tubes which are a compromise between the electrometer tube and the more or less standard triodes. Typical tubes are the

Fig. 35.—Characteristics of tube with low grid currents.

RJ-550 and RJ-553 which have grid currents of the order of 0.01 μa. and input resistance of the order of 5×10^8 ohms.

The Western Electric Company[1] has developed an electrometer tube known as type D-96475, and an experimental tube of this general type has been designed by RCA known as A-154. The following data are taken from the Western Electric bulletin:

The tube itself should be mounted in a container which shields it from light and from stray electric fields. In order to minimize insulation leaks it is well to keep the circuit ground at the average potential of the control grid. It may also be necessary in some cases to clean the outside of the bulb carefully and to keep the air surrounding the tube free from moisture by means of a drying agent such as calcium chloride or phosphorus pentoxide in the same container. A grounded

[1] Pemick, D. B., D.C. Amplifier Circuits for Use with the Electrometer Tube, *Rev. Sci. Instruments*, April, 1935. This applies to the Western Electric tube D-96475.

guard ring or band of aquadag or tin foil around the bulb from base to center is useful and sometimes necessary to reduce the leakage across the surface and help dissipate charges which may collect on the bulb.

The tube itself has a 1.0-volt filament consuming 0.27 amp. and operates with 4 to 6 volts on the plate taking 85 to 410 ma. with an inner grid voltage of 4 to 6. With a control grid bias of -3, inner grid currents of 520 and 910 μa., respectively, under the two preceding conditions, the mutual conductance is 40 to 96 ma. per volt, and the input resistance is 10^{16} and 10^{15} ohms.

Photometry of Stars.—As is to be expected, the FP-54 associated with a sensitive photocell has been applied to the photometry of stars.[1] In the *Astrophysical Journal*, November, 1932, Albert E. Whitford relates preliminary results of such a combination in use at Washburn Observatory. The grid resistor had a value of 10^{10} to 10^{11} ohms and current flowing through it affected the grid bias of the tube and hence the plate current. This variation was caused by the light of the star illuminating the photocell (a Kunz potassium hydride cell).

The photocell and amplifier tube were placed in a container and evacuated to 10^{-2} mm. of mercury thereby reducing random fluctuations by a factor of 10. (Others have noted the benefit of mounting the FP-54 in a vacuum.) With a galvanometer of sensitivity 2.6×10^{-10} amp. per millimeter at 3 m., an input or grid resistance of 8.8×10^{10} ohms, the voltage sensitivity of the system was 95,000 mm. per volt, current sensitivity of 1.2×10^{-16} amp. per millimeter, and the current amplification 2.2×10^{16}.

The working limit of the system involving the 15-in. telescope was put at magnitude 9.0 as against the magnitude of 7.5 with the cell and Lindemann electrometer. "Needless to say, this gain of 1.5 mag., a four-fold increase in sensitivity, has opened up for our telescope a field of work hitherto quite inaccessible," quoting Dr. Stebbins of the Washburn Observatory.

The Vacuum-tube Voltmeter.—An important piece of laboratory equipment is a tube voltmeter. It is really a rectifier in which the input voltage causes a change in plate current. This change in plate current is calibrated in terms of the input voltage. There are many forms of the vacuum-tube voltmeter, some simple, some complicated, some compensated against variations

[1] On the value of electronics in astronomy, see *Phys.*, June, 1932, p. 418.

of battery fluctuations and other variables. The literature is replete with references to the voltmeter of these types; all laboratories working at low or high frequencies employ them.

The input voltage may be direct or alternating current, the voltmeter may be calibrated in r.m.s. or peak values; rectification in the tube may take place in the grid or the plate circuit; the steady no-signal plate current may be balanced out of the d.c. plate meter so that its entire scale will be useful. It then reads automatically the change in current produced by the input signal. This balancing out·may take place mechanically, *i.e.*, by turning back the pointer of the meter so that it registers zero even when a slight current flows through it; or electrically, as by a bucking battery.
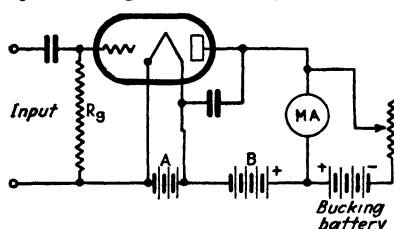
FIG. 36.—Grid-circuit detection used as vacuum-tube voltmeter.

The set-up may be arranged so that maximum current flows when no signal is applied and any input, therefore, will decrease the meter reading. This connection prevents damage to the meter by application of too great an input voltage.

In general the range in voltage that can be handled without making adjustments to either the grid bias or the plate voltage is about 3 to 1, *i.e.*, from 1 volt to 3 volts, from 3 volts to 9 volts, etc. This restricted range is partly due to the fact that the meter is a square-law device, tripling the input voltage producing 9 times the current, and the fact that the meter cannot be read accurately at low values of current; and partly due to the fact that it is difficult to make certain that the no-signal plate current has been just balanced out and no more.

The grid-circuit detection meter is shown in Fig. 36. Here the grid is connected, through a resistor, to the positive (or negative) terminal of the battery. The current flowing through this resistance fixes the actual voltage on the grid with respect to the cathode. This is adjusted so that the best part of the grid-current characteristic is chosen, *i.e.*, the point of greatest curvature where the maximum rectification will occur.

Rectification in this circuit produces some d.c. grid current which, flowing through the grid resistance, changes the steady grid bias. This change in grid bias is reflected by a corresponding

change in plate current which is read on the meter. The condenser in the input is to provide a path of low impedance for the signals (if a.c.) and to prevent direct current from flowing through the circuit under test. At the same time, if direct current is flowing in the external circuit, the condenser will prevent it from flowing through the grid resistor and thereby disturbing the adjustment of the grid bias.

Because of the fairly low input impedance of such a detector, due to the positive grid, the circuit is not used so often as is the scheme described below where plate rectification takes place. The grid-circuit detector, however, is more sensitive. This means simply that a smaller input voltage is necessary to produce a given plate current change.

Plate-circuit Rectifier.—In cases where the input impedance of the tube is to be kept as high as possible so as not to disturb the
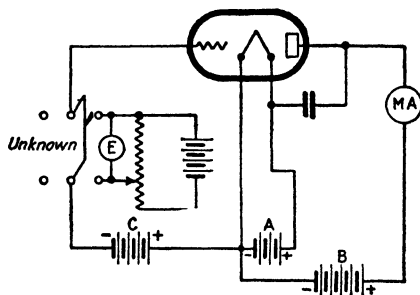
Fig. 37 —Voltmeter of plate-detection type.

circuit under investigation, the plate-circuit or grid-bias rectifier is employed. In this case (Fig. 37) the grid is simply so biased that with the applied plate voltage a curved part of the characteristic is utilized. This means that the tube is usually heavily biased, so that little current flows in the plate circuit until some signal is applied. The actual value of bias may be adjusted by means of a potentiometer so that the point of greatest curvature is used and this bias may be obtained from batteries or due to the filament current flowing through a resistor, or to the plate current flowing through a resistor in series with the filament.

In general the bias is chosen by the input signal to be measured. Thus if the input peak signal is to be 9 volts, this d.c. voltage, or slightly more, is applied to the tube. Then the

plate voltage is chosen so that either a given voltage produces the greatest value of plate-current change, or so that the 9-volt signal will just bring the plate current to the full-scale deflection of the meter.
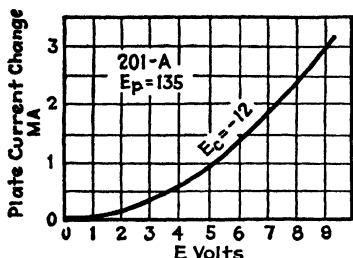
FIG. 38.—Calibration of typical vacuum-tube voltmeter.

A Comparison Voltmeter.—The vacuum-tube voltmeter may be used in another way. After the input voltage has been applied and the plate-current reading noted, this unknown voltage may be removed and a battery and potential divider substituted. By adjusting the slider so that the same plate-current reading is secured, the calibrating voltage is now equal to the unknown voltage and may be read with an ordinary a.c.-d.c. meter.

The Slide-back Method.—Still another method has been used very often. The plate current is reduced to some arbitrary easily readable value by adjusting the grid bias. Then the input voltage is applied and the resulting plate current again reduced to the exact value it had before the unknown was applied. The voltage required to reduce the plate current to its no-input value is taken as the equivalent of the unknown voltage. The difficulty with this method lies in the operator's lack of ability to tell exactly when he has brought back the current to the original value.

Single-battery Voltmeter.—A method whereby a single block of battery, say of 22.5 volts, may be used is shown in Fig. 39.[1] The

FIG. 39.—Single-battery voltmeter.

grid bias is due to the filament current flowing through the resistance in the filament lead; the zero of the no-input plate current is suppressed from the indicating meter by the balance of the bridge.

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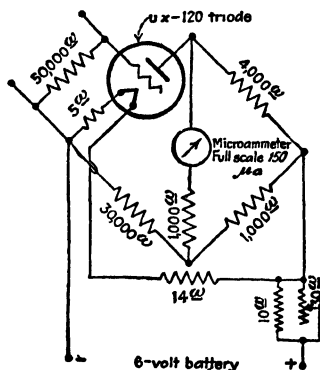
[1] HOARE, S. C., *J. Am. Inst. Elec. Eng.*, vol. 46, p. 541, 1927.

Amplifier Voltmeter.—The grid rectifier will measure voltages of the order of a few tenths of a volt; the plate circuit rectifier will go down to a half volt and up to several volts; the slide-back voltmeter will read voltages of several volts up to 40, 50, or more, and more or less fits into the gap between the other tube voltmeters and the electrostatic voltmeter.

To measure voltages smaller than those above an amplifier made by General Radio and consisting of two stages of triode amplification coupled to each other by a resistance-capacity network has a voltage amplification of between 100 and 200 between 25 cycles and 50 kc. The amplification depends upon the resistance of the final voltmeter which is placed across a load resistance in the plate circuit of the final amplifier. With a voltmeter giving full-scale deflection on 2 volts, an input voltage of 20 mv. will produce full-scale deflection and 2 mv. may be detected.

Self-biased Voltmeter.—If the direct current produced by the rectification process is caused to flow through a resistance in such a direction that the grid circuit of the tube may be connected to the negative terminal of this resistance, the tube becomes an

Fig. 40.—Self-biased voltmeter.

automatically biased detector. Thus when a signal is applied and plate current flows through the bias resistor, the grid becomes more negative preventing the plate current from rising as high as it might with a fixed bias. The greater the input voltage and the corresponding plate current, the greater will be the bias on the grid. The characteristic is longer and covers a wider range than that of the usual voltmeter.
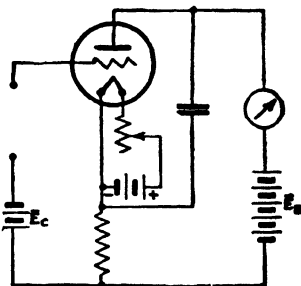
Multi-range Amplifier Voltmeter.—An amplifier voltmeter which seems to be free of many of the limitations of former instruments has been described.[1] Its over-all dimensions are 7¾ in. long, 6 in. wide, and 6 in. high. Only one 45-volt B battery is required, although any source of continuous current capable of supply 50 to 60 ma. at 38 to 50 volts will be found satisfactory. It is accurate at both radio and audio frequencies;

[1] TULAUSKAS, L., A Multi-range Vacuum-tube Voltmeter, *Electronics*, July, 1930, p. 170.

no corrections are required. It covers a relatively large range—up to 12 volts peak—and has only one main adjustment.

The theory is that of an overbiased tube in which an input voltage does not produce a symmetrical wave of plate current but a distorted wave. In this process the positive half of the a.c. plate current *increases* from the no-signal current more than the negative half-cycle *decreases*. The result is a production of some direct current which added to the no-signal value increases the latter. This increase is a function of the amplitude of the input applied signal.

It is difficult to utilize this principle directly as the plate-current change is small, requiring the use of a microammeter.
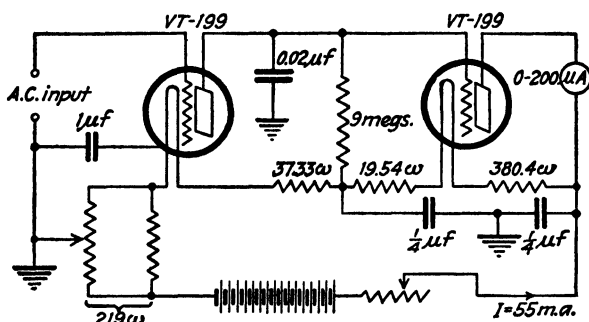
Fig. 41.—Amplifier-voltmeter with a single battery.

As the initial plate current is large in proportion to its variation, some means must be employed to utilize the variation only. This is done, as usual, by a bucking battery whereby the steady plate current is balanced out and the increase over that value operates a microammeter. Unfortunately, such a device is subject to "drift," *i.e.*, variation of the zero point. It is a scheme which is widely used, however, and in spite of all its faults is capable of fair results in experienced hands.

If a direct-current amplifier is connected to the output of the rectifier, the output of the amplifier will vary in proportion to the amplitude of the alternating current impressed on the rectifier grid. Only the variation in plate current is utilized as the grid bias on the amplifier compensates the no-signal rectifier plate current which tends to reduce the amplifier grid bias. Furthermore, the variations are amplified many times,

wherefore a meter of lower sensitivity may be employed. Such an arrangement is shown in Fig. 41.

The 199-type tube requires only 60 ma. for its successful operation and will give satisfactory operation with as little as 50 ma. through the filament. For that reason, two of these tubes were used.

As a preliminary adjustment, it is advisable to use the values of resistance given in Fig. 41. The rectifier load resistor is not critical; it may be any value from 4 to 10 megohms. A milliammeter is placed in series with the 45-volt B battery, and during all the adjustments care must be taken that the current in that circuit never exceeds 60 ma.

A Diode-triode Peak Voltmeter.[1]—A diode employing a large bias-producing resistor yields a current proportional to the peak of the applied voltage over a wide range. The current for nominal voltages is low in such a diode, but a d.c. amplifier overcomes this difficulty, making it possible to use an inexpensive indicating meter. The meter to be described gives full-scale reading on a 500-μa meter for 1 volt peak applied. Figure 42 shows a type-30 tube acting as a diode rectifier charging condenser C,
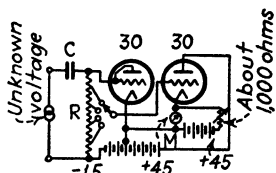
Fig. 42.—Diode-triode voltmeter.

which in turn discharges at a steady rate through resistor R. For true peak voltage indication R should have several megohms total resistance. The second tube, which may also be a type 30, acts as a d.c. amplifier. A point on R is selected by means of the tap switch, such that the d.c. drop applied to the grid of the second tube gives a current change within the meter range. Since the taps are for d.c. voltage division only, this system introduces no frequency discrimination. The maximum voltage measurable by this method is determined by the inverse peak of the rectifier, which is of the order of a few hundred volts in the case of receiving-type tubes.

The diode plates of a duplex triode or pentode may be used as the diode peak rectifier in place of the first 30 tube, and the triode or pentode elements may be used as the d.c. amplifier.

Figure 43 shows a power-operated voltmeter utilizing a 55 tube. The bias on the diode is for the purpose of reducing its initial

[1] BARBER, A. W., *Electronics*, October, 1934.

current to zero; otherwise changing the range switch position changes the steady current in the meter and hence requires readjustment of the bucking current resistor R'.
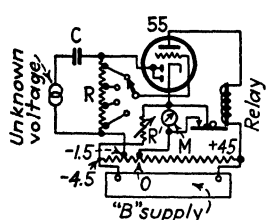
Fig. 43.—Voltmeter operated from one battery.

Since the diode bias is also the d.c. amplifier grid bias, a plate voltage of 45 volts is chosen which gives a point on the linear part of the plate-current grid-voltage characteristic of the tube. The calibration curves shown are of the meter of Fig. 43.

The relay shown in the plate circuit is for the purpose of protecting the meter while the tube is warming up. Inasmuch as buck-ing current would normally flow through the meter as soon as the power is turned on, the relay is connected to short the meter with no current flowing in its windings. When the plate
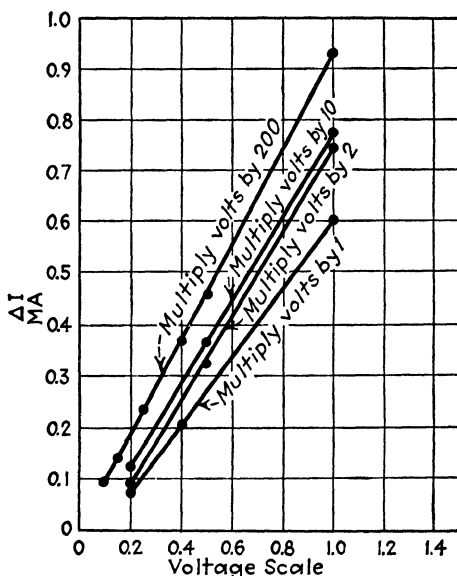
Fig. 44.—Calibration of voltmeter of Fig. 43.

current reaches a point where the bucking current minus the plate current can be safely passed through the meter, the relay operates and unshunts the meter.

Other tubes than the 55 may be used in this voltmeter. In choosing a tube, however, it should be remembered that the plate-current variation must be linear over the range of rectified voltages plus unrectified alternating current, since the a.c. voltage is applied to the d.c. amplifier grid. Plate rectification of the a.c. voltage under certain conditions may largely offset the effect of the diode rectification since the two have opposite effects on the plate current.

To conclude, the diode-rectifier d.c. amplifier vacuum-tube voltmeter reads peak volts, covers a wide range of voltages, has a linear scale, uses an inexpensive current meter, and has an excellent frequency characteristic.

Thermocouple Voltmeter.—Figure 45 shows a circuit[1] whereby the grid of a high-vacuum amplifier is directly coupled to a
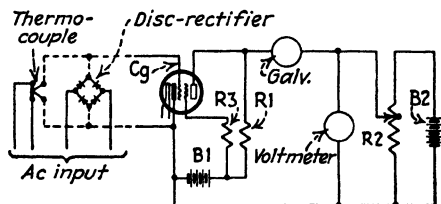
FIG. 45.—Method of amplifying output of thermocouple.

thermocouple or copper oxide rectifier. Here any change in potential in the control grid produces a corresponding change in tube plate resistance and a voltage-drop change across R_1 which is noted by the galvanometer reading.

R_2 then is varied until a balance is again obtained. The difference in voltage may be noted on the voltmeter as a measure of the input voltage.

An A.C. Bolometer.[2]—This device consists of a bolometer followed by a vacuum-tube amplifier and with a 0.0016-in. tungsten wire has a sensitivity of 0.068 volt per watt per square centimeter.

Radium Measurement.—The measurement of radium-emanation implants had been accomplished by dropping the implants into an ionization chamber which sends a current surge through a two-stage d.c. amplifier and into a Leeds and Northrup type-P

[1] MURRAY, CHARLES, *Electronics*, June, 1935, p. 190.

[2] MOON, PARRY, and W. R. MILLS, JR., *Rev. Sci. Instruments*, January, 1935.

galvanometer. With a galvanometer sensitivity of 10^{-9} amp. per millimeter and a period of 12.5 sec. an over-all sensitivity of 5 cm. per millicurie was obtained, types-30 and -32 tubes being used. A linear response was obtained up to approximately 4 millicuries.[1]
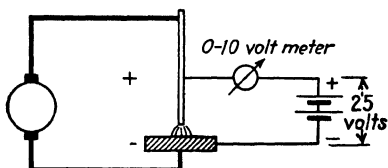
FIG. 46.—Elements of welding meter.

Tube Voltmeter Applied to Arc Welding.—In arc welding the length of the arc between the workpiece and electrode is important when uniform and satisfactory results are desired. This length is related to the voltage across the arc. The open-circuit voltage, however, may be twice that when the arc is struck, so that an ordinary voltmeter is not very satisfactory as a measuring device for this job. A voltmeter that would read only between 25 and 35 volts is needed.

A practical solution to this difficulty is a vacuum-tube voltmeter as worked out by Richter.[2] By the potentiometer R_1R_2
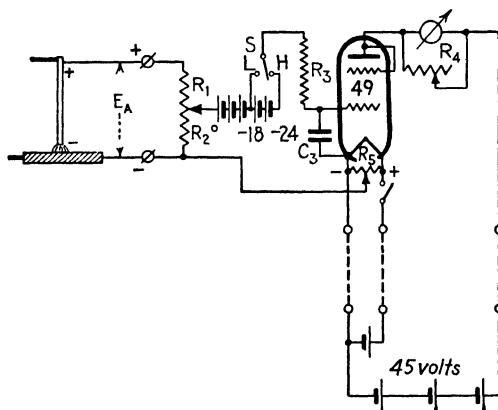
FIG. 47.—Voltmeter details, used for welding control.

only half the arc voltage variations are impressed on the tube. By tapping the C battery various ranges may be obtained. Thus if the arc voltage varies from 32 to 44 volts, the bias on

[1] MacDonald, P. A., and E. M. Campbell, *Rev. Sci. Instruments*, August, 1935.

[2] Richter, W., *Electronics*, March, 1935.

the tube varies from -7 to -1 volts. R_4 and R_5 provide adjustments to avoid recalibration when tubes are changed.

An Alternating-current Galvanometer Using Amplifier Tubes. A useful amplifier voltmeter for use in balancing a Wheatstone bridge, or for production testing, is shown in Fig. 48. In this case the amplifier takes the place of the galvanometer which is placed in the plate circuit of the detector after the bridge voltages have been amplified. Thus the instrument becomes a voltmeter detector. It is a.c.-operated.
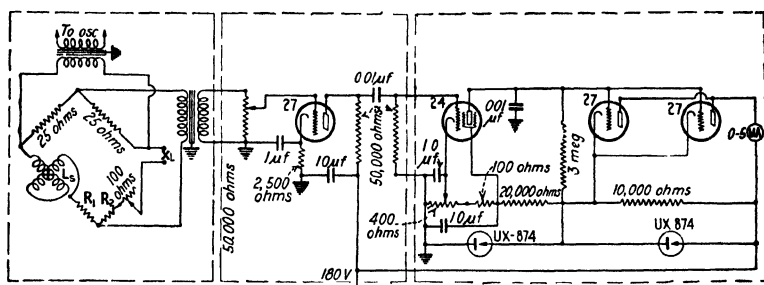
Fig. 48.—Bridge-balance indicator using amplifier voltmeter.

A typical example of the sensitivity obtainable in this manner is cited:[1]

A General Radio capacity bridge, type 383-B, used for measuring small capacities to 600 $\mu\mu f$ is equipped with a large main dial and a smaller vernier dial. With headphones attached to the output of that bridge an apparent null was obtained and no change could be heard by moving the vernier dial from one end of the scale to the other. The a.c. galvanometer was then connected in place of the phones and a movement of one division on the vernier dial resulted in a 20-per cent change in the reading of the milliammeter.

High-resistance Measurement.—Preisman[2] has patented under U.S. No. 1,966,185 a method of using a free or floating grid with a high-vacuum tube as an ohmmeter for measuring high resistances. The plate circuit of the tube is conventional, employing a galvanometer in series with the plate battery. Between the grid and cathode is connected the resistance to be measured, with a high-voltage battery poled so that the grid is positive.

[1] TULAUSKAS, L., *Electronics*, January, 1931.
[2] PREISMAN, ALBERT, *Electronics*, July, 1935, p. 214.

For finite values of the unknown resistance the grid discharges through the resistance, aided by the grid battery. The virtue of the battery is that the increase in plate current for a given value of the unknown resistance is greater, thereby improving the sensitivity of the device. An empirical relation may be found between a series of known resistances and the plate current for any value of grid voltage. This relation may be used to calibrate the plate-circuit meter in terms of resistance. Preisman recommends a type-40 tube with 90 volts on the plate, approximately 1,000 volts in the grid and a 0–1 ma. plate meter. Such a device will read up to 1,000 megohms or higher. The grid voltage may be decreased if the plate circuit is arranged so that the plate meter reads only the change in plate current. It is possible to operate the device from alternating current.

An Inexpensive D.C. Amplifier.—A 2A6 tube properly balanced[1] gives a stable voltage sensitivity of 100,000 mm. per volt
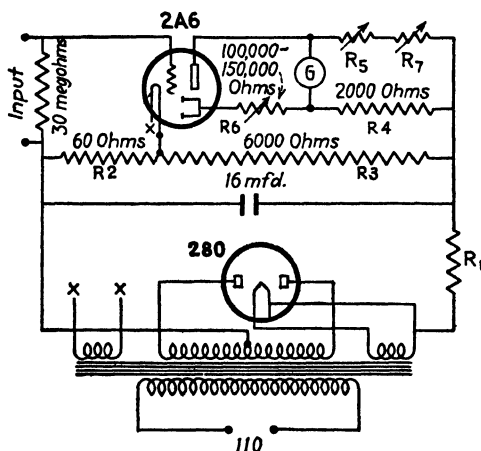
Fig. 49.—A.c.-operated d.c. amplifier.

with an ordinary wall galvanometer and permits measuring of currents in the order of the magnitude of 10^{-13} amp. If used in connection with a microammeter and simple rectifier, it makes a very convenient portable instrument which can be operated from the a.c. outlets directly to measure currents of the order of 10^{-11} amp. or as a voltmeter with a voltage sensitivity of 1,000 mm. per volt.

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[1] HUNTOON, R. D., *Rev. Sci. Instruments*, vol. 6, p. 322, October, 1935.

The circuit can readily be balanced by varying R_6 (Fig 49) until changes in plate voltage have little effect on the galvanometer. At the start R_6 should be larger than necessary, say 150,000 ohms, and the filament voltage considerably lower than normal. The emission should be slightly increased, and the galvanometer kept near zero by controlling R_5. In the balance point the galvanometer will reverse its deflection for an increase of emission. The fixed balance ought to occur with subnormal filament voltage R_6 may then be decreased by 10,000 ohms, and any higher balance point determined. This is repeated until the balance occurs at rated filament current.

The portable circuit showed a sensitivity of 3×10^{-11} amp. per millimeter with a Weston model-441 portable galvanometer of sensitivity of 2.5×10^{-7} amp. per millimeter requiring only about 10 min. to warm up sufficiently. No shielding was necessary when one end of the input was grounded. When carefully balanced and shielded the amplifier gave a stable sensitivity of 3×10^{-13} amp. per millimeter. In this case a wall galvanometer with a sensitivity of 10^{-8} amp. per millimeter was used.

Automatic Volume Control.—Two general circuits taken from the radio art are described here because of their intrinsic interest and their possible employment in laboratory or industrial problems. These are, first, the automatic control of the volume (power output) of a receiver by means of a vacuum-tube rectifier or voltmeter; and, secondly, the automatic suppression of undesired extraneous signals. It is quite possible that either or both of these interesting circuit phenomena could be employed in other than communication devices.

A radio receiver gets its input from an antenna-ground system. This input voltage is frequently very small, of the order of a few microvolts, but as the receiver is tuned from one channel to another, the voltage secured from various stations may vary over very wide limits. Furthermore, the field strength (volts) secured from a distant station varies from moment to moment during night time due to the phenomena of fading. This is caused by interference between a wave directed along the ground to the receiver from the transmitter and a wave directed upward to the sky and reflected down to the receiver from a moving horizontal layer of ionized particles perhaps 100 miles above the earth.

Therefore the signal strength emanating from the receiver varies not only from channel to channel but from moment to moment on a given channel. The listener, having set his volume control to a desired level, will get blasts of volume when he has tuned his receiver to a powerful local transmitter or weak signals when he tunes to a distant station. This is not only annoying but dangerous to the supports of the moving part of the loud-speaker.

Therefore a system has come into very wide use which maintains the output of the receiver more or less constant regardless of the input voltage. Such a system is called automatic volume control or simply a.v.c. The mode of operation is as follows:

Input

To grids of tubes under control
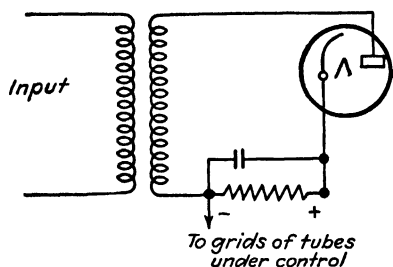
Fig. 50.—Diode used as automatic volume-control tube.

The input signals are amplified as much as desired and are then put into a rectifier. In this rectification process a certain amount of direct current is produced which is made to flow through a resistor. One end of this resistor is naturally more negative than the other. This negative end is connected to the control grids of the various amplifier stages in such a direction that strong signals increase the negative bias on the amplifier tubes and weak signals decrease the negative bias.

Now the amplification secured from each tube is a function of the mutual conductance of each tube, and this, in turn, is a function of the negative bias on the tube, a high bias (due to strong incoming signals) producing a low mutual conductance and therefore a low order of voltage amplification.

If desired the d.c. voltage to be used for automatic-volume-control purposes may be amplified in a d.c. amplifier before application to the amplifier grids. The order of control depends, of course, upon various factors, but with modern tubes the output of a receiver may be maintained constant over input variations of 100,000 to 1 in input voltage. The time rate at which the amplifier has its gain changed as the input voltage changes may be varied so that slow changes only are effective in decreasing or increasing the mutual conductance of the tubes; or the amplifier gain may be made to follow rapid changes.

By means of, a variable-mu tube with an exponential characteristic the relation between gain and input voltage may be made exponential over a very wide range (see Chap. III). By putting a fixed bias upon the rectifier which prevents the production of direct current until a certain limiting lower limit of input voltage is impressed upon this tube, the automatic volume control action may be delayed. Such a system is known as "delayed automatic volume control."

While automatic-volume-control systems have not come into much use industrially, there have been a few applications of the principle. For example, a.v.c. may be employed to keep a control circuit in condition regardless of other varying conditions. Let us assume that temperature is to be controlled regardless of the humidity. Now, a circuit might be set up which would be sensitive to both temperature and humidity and which, if humidity variations could be eliminated, would perform the temperature-control function perfectly. If, however, another circuit may be set up which is sensitive only to humidity and which produces a variable d.c. voltage by an a.v.c. phenomenon as the humidity changes, this variable voltage may be used to keep the temperature-control apparatus independent of humidity. Of course other variables than temperature and humidity may be operated upon in this manner.

Such circuits need not be complex. Popular radio-receiving tubes such as the 55 include both a triode (which might control the temperature) and a diode (which might furnish the variable d.c. voltage from humidity variations).

The second of these communication circuits which may be useful in industrial application is that of "noise suppression." Again consider a superheterodyne receiver. With no incoming signal to be rectified and thereby to reduce the amplification of the tubes, the over-all amplification of the receivers is very great. Therefore it is likely to pick up undesired noises. Tuning such a receiver is really jumping from a station, across a gap filled with noise, to another station. It would be desirable to eliminate this noisy region.

Suppose one of the amplifiers which comes after the detector, *i.e.*, an audio-frequency amplifier, is so operated that, when the preliminary amplifiers are operating at maximum gain, this audio amplifier operates at minimum gain. Then when a station

is tuned in, the gain of the preliminary amplifiers is reduced, and the gain of the audio amplifier is increased.

Actually the audio amplifier is shut off completely between desired stations, and it is only when the operator has tuned the set to the vicinity of the desired station that the loud-speaker gives out any signal at all.

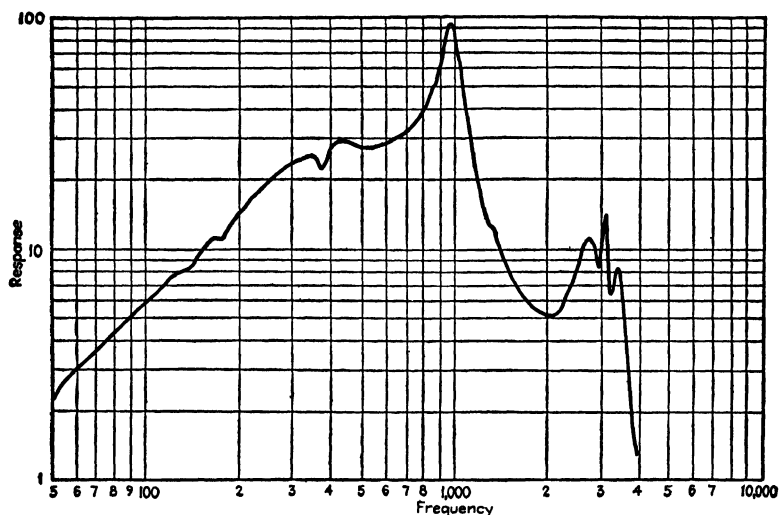**Logarithmic Recording System.**—Taking advantage of the characteristics of variable-mu screen-grid tubes and of an auto-

FIG. 51.—Response of head telephone (509W) made with Ballantine recorder.

matic-volume-control system, a method of recording current or voltage variations (or other variable translatable into current or voltage changes) has been developed permitting records to be made over a wide range (40 db. or 100 to 1 in voltage).[1]

The basic element is an amplifier tube in which the amplification is an exponential function of the control-grid bias. Several of these tubes are cascaded and in turn operate a rectifier whose d.c. output is impressed upon the control grids of the previous tubes (as in a conventional automatic-volume-control system) so that the output voltage tends to remain constant. The recording meter reads the variations in automatic-volume-control voltage necessary to maintain the output voltage constant.

[1] BALLANTINE, STUART, *Electronics*, January, 1931; *J. Optical Soc. Am.*, July, 1933.

The deflection of this voltmeter is proportional to the logarithm of the input voltage.

The same effect may be secured by operating several tubes in parallel, the amplification factors of the several tubes being widely different. At high values of control-grid bias the plate currents of the tubes with high mu-factors will be low or zero and all the current will be produced by the low-mu tubes. By carefully choosing the mu-factors of the several tubes (or by properly designing the single variable-mu tube), the mutual conductance of the system may have almost any desired form with respect to the input voltage.

Following Ballantine's early work on logarithmic amplifiers, Hunt[1] produced amplifier voltmeters covering very wide ranges with a response of this type. Fundamentally the circuit is composed of a variable-mu tetrode acting as amplifier working into a diode detector acting as rectifier. Two tubes permit a range that is linear (in decibels) from approximately 5 db. below to 15 db. above 1 volt. If a greater range is to be covered, the amplification must be increased and a cascaded pair of variable-mu tubes are used, each operating a rectifier or diode plate. The tubes are connected together by a resistance-capacity network.

The voltages produced by the second tube are rectified first, *i.e.*, at lower values of input voltage to the amplifier. As higher and higher input voltages are applied, the second-tube output begins to flatten off due to overloading, but by this time the voltages produced in the output of the first amplifier become sufficient to operate the diode plate assigned to the first amplifier and contribute to the rectified current.

The diagram given in Fig. 52*A* is a three-stage system using three amplifiers each with its own diode rectifier. As seen from the calibration curve, the amplifier voltmeter is linear in decibels over the wide range of 80 db. This represents a voltage ratio of 10,000 to 1, that is, from 0.1 millivolt to 1 volt.

Tubes of the 39, 35, 58 types have been used as the amplifiers while the complicated combinations of diode and triode or pentode introduced to the radio trade in 1932 and 1933 have been used as the detectors (types 85, 75, 55, etc.).

[1] HUNT, F. V., Vacuum-tube Voltmeter with Logarithmic Response, *Rev. Sci. Instruments*, December, 1933.

Measurement of Low Voltages.—To any voltmeter an amplifier may be added which will increase the range. It is not difficult to increase the range of a.c. instruments by means of an amplifier. As a matter of fact, high-frequency voltages can be
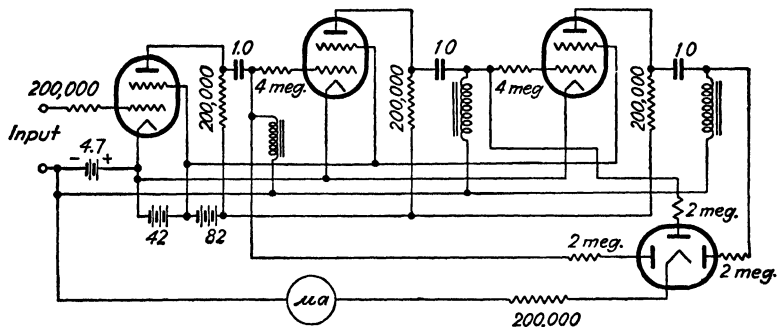
FIG. 52A.—Logarithmic amplifier voltmeter of wide range.

measured in no other way than by first amplifying and then rectifying them to operate a d.c. meter.

By making the amplifier cover only a small range of frequencies to keep out extraneous noise voltages, etc., high-frequency voltages of the order of 1 μv and at lower frequencies of the order of $\frac{1}{10}$ μv may be measured.

Measuring very small direct voltages, however, is another matter, and some progress is being made toward extending the range of electronic electrometers and other sensitive instruments. Converting the voltages into alternating voltages or into voltages with a.c. components and then amplifying them has been tried with some success.
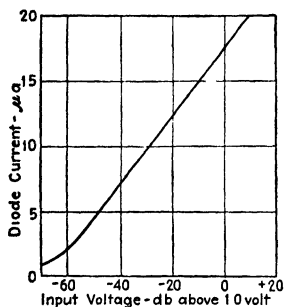
FIG. 52B.—Wide linear response of Hunt's voltmeter.

A Multiplier for Currents from a High-impedance Source.—Figure 53[1] shows a vacuum-tube current-multiplier circuit which will multiply a small direct current from a high-impedance source, by a definite factor which is practically unaffected by the tube characteristics or by supply voltage variations. Essen-

[1] SHEPARD, F. H., Inst. Radio Eng. Convention, Cleveland, May 11, 12, 13, 1936.

tially the operation of the circuit is as follows: The signal current I_1 is used to discharge condenser C_1; after the charge on C_1 has been reduced to a certain value the potential on the grid of the buffer stage (2A6) will be such as to allow the current through the buffer stage to be sufficient to create enough voltage drop across the cathode load resistor to decrease the bias on the 885 gas triode enough to cause the tube to "break down"; when this occurs, condenser C_2 is discharged and then charged in the
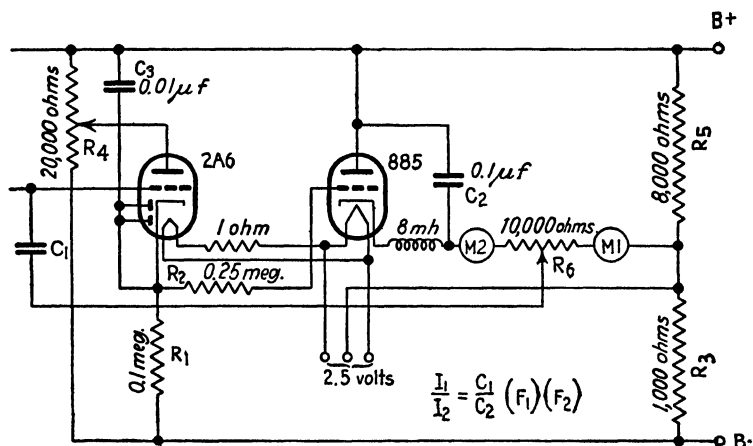
Fig. 53.—Shepard's current multiplier.

opposite direction to a value equal to E_1 minus the tube drop (15 volts) times two; this exact value is unimportant. While condenser C_2 is being discharged through the 885, C_3 holds the cathode of the 2A6 at an essentially constant potential, and C_1 is charged to a potential equal to the potential change across C_2, modified by a factor F_1 determined by the position of the slide on R_6. This is true when the plate potential of the 2A6 is adjusted so that the 885 breaks down at the instant that the control grid starts to draw grid current. This adjustment can be made by varying the slide on R_4 until the 885 ceases to relax and then backing off on the control slightly. The output meter M_1 reads $I_2 + I_1$, and the output meter M_2 reads $I_2 - I_1$; but as I_1 is usually extremely small compared to I_2, $I_1 + I_2$ and $I_2 - I_1$ can be generally considered equal to I_2, and the equation

$$\frac{I_1}{I_2} = \frac{C_1}{C_2}f_1$$

can be written without appreciable error as

$$\frac{I_1}{I_2 + I_1} = \frac{C_1}{C_2}F_1,$$

or

$$\frac{I_1}{I_2 - I_1} = \frac{C_1}{C_2}$$

These equations hold true only when the actual discharge time for the 885 is extremely small with respect to the time taken to build up the charge on condenser C_2 through resistor R_6. This is generally the case. Where a high degree of accuracy is required a correction factor F_2 to account for the time required for discharge should be applied to the reading of the output meter. This correction factor, which is slightly less than 1, will apply for all readings of the instrument.

It should be noted that the grid-to-cathode and grid-to-plate capacities of the 2A6 or any capacities in the input circuit are not to be considered a part of C_1 in the computation of the current ratios in the circuit. When the 885 discharges C_2, C_1 is charged as explained above to a voltage equal to the voltage change across C_2 times F_1. After C_2 is allowed to charge back to normal through resistor R_6, the charge across C_1 is allowed to distribute itself between C_1 and C_x without changing its actual value. C_x is the sum of all the capacities from grid to ground; this includes the capacities of the grid to plate and grid to cathode of the 2A6 and the capacities in the signal-current source. Since this is true, a definite current will remove this charge in a definite time regardless of the size of C_x.

The most accurate form of the expression for current ratios in this circuit is

$$\frac{I_1}{I_2} = \frac{C_1}{C_2}(F_1)(F_2).$$

The accuracy of this formula is probably as great as the accuracy of the reading of the output meter, when I_2 is equal to the meter reading M_1 minus I_1, or I_2 is equal to $\dfrac{M_1 + M_2}{2}$, when F_1 is a correction factor due to the setting of the slider on potentiometer R_6, and F_2 is a correction factor due to the time of conduction per cycle of the 885.

It is interesting to note that practically all of the time C_1 is being discharged by means of I_1 the plate current of the buffer stage is zero. This means that there can be no gas current to the grid during this time. The heater voltage of the buffer stage is
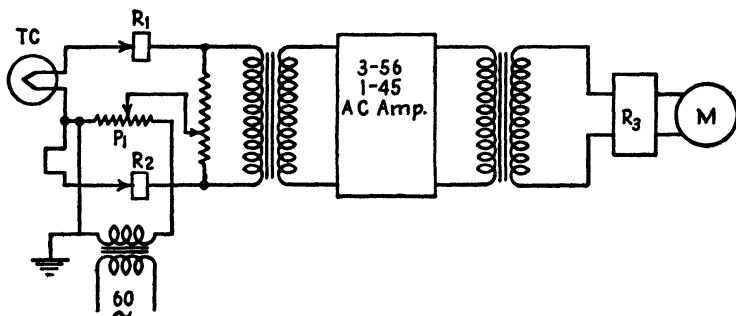
FIG. 54.—Method of amplifying output of low-impedance thermocouple by modulating it and using an a.c. amplifier.

lowered to reduce the grid emission, and the heater is returned to a potential positive with respect to the grid of the buffer stage to avoid the possibility of emission from the heaters to the grid. This circuit finds its application in the measurement of small phototube currents, in the measurements of leakage currents, or in any other small currents in high-impedance circuits. If test condensers are connected in place of C_1, I_1 will
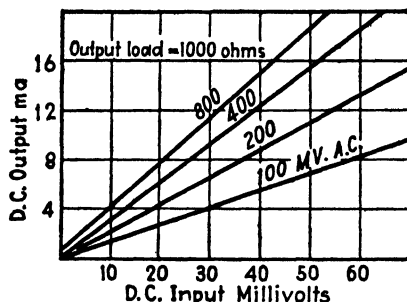
FIG. 55.—Calibration of Razek amplifier.

be proportioned to the leakage of the condenser expressed directly in units of resistance per unit of capacity.

Razek[1] has developed a simple means for amplifying small direct voltages by combining them with an alternating carrier

[1] RAZEK, JOSEPH, A Vacuum Tube Amplifier for Small Direct Voltages, *J. Franklin Inst.*, February, 1935, p. 137.

of the same order of magnitude. The voltages are then passed through a copper oxide rectifier which suppresses one part of the cycle. The degree of suppression depends on the magnitude of the direct voltage. The resulting fluctuating voltage can be amplified to any desired degree by conventional methods. By his method it is possible to amplify voltages developed by thermocouples or galvanometers. For example, he cites the possibility of amplifying the galvanometer current of 5 ma. to a current of 50 milliamp. into 1,000 ohms. The circuit and a typical calibration curve are shown.
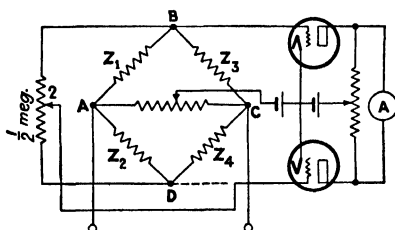
FIG. 56.—Bridge-balance indicator of high sensitivity.

Bridge-balance Indicator.[1]—An excellent method of increasing the sensitivity of a.c. bridges in measurements is to connect two vacuum tubes in push-pull across the output of the bridge so that, when balance exists, a sensitive meter shunted across the output of the two plates reads zero. To understand the principles of the circuit shown, first regard potentiometer 2 as being disconnected from the circuit and the grid of the lower tube connected directly to the bridge as shown by the dotted line. Then with the common grid return set at A by the slider, null reading on the meter indicates voltages of equal magnitudes across Z_1 and Z_2. With it set at C, null reading shows equal

[1] McNamara, F. T., *Rev. Sci. Instruments*, vol. 2, no. 6, pp. 343–347, 1931.

The Central Scientific Company has an impedance bridge using a somewhat similar circuit originally developed by Van der Bijl, modified by A. L. Fitch as a vacuum-tube potentiometer (*J. Optical Soc. Am. and Rev. Sci. Instruments*, vol. 14, p. 348, 1927), and G. A. Stone as an impedance bridge (*J. Optical Soc. Am. and Rev. Sci. Instruments*, vol. 19, p. 326, 1929) in which the resultant impedance is given as the square root of the product of two impedances. A description will be found in the *Bulletin* of the Central Scientific Company (U. S. Patent 1,919,538). The constants of amplifier and galvanometer circuits to be used with a.c. bridges, particularly the Schering bridge, will be found in *Gen. Elec. Rev.*, May, 1934, p. 224, by W. A. Ford and H. W. Bousman.

magnitudes across Z_3 and Z_4. A null reading at both settings indicates that B and D are 'at the same potential and that the voltages are balanced in magnitude and phase.

Using tubes as detectors in this method gives very good sensitivity in detecting balance because the meter indication is proportional to the difference of the squares of two voltages. Thus, if the voltages across Z_1 and Z_2 are 5.1 and 5.0 volts, respectively, the meter indication is proportional to

$$5.1^2 - 5.0^2 = 1.01 \text{ (volts)}$$

This far exceeds the sensitivity of most other tube methods which give a meter reading proportional to the square of the difference, 0.01 volt, or the sensitivity of indicators like a telephone head set or a vibration galvanometer whose indication is directly proportional to the difference, 0.1 volt.

Where very high precision is desired, this is the method to use; but it requires tubes with identical characteristics. To get around this difficulty, potentiometer 2 is inserted. The result is a sacrifice in sensitivity but the precision is still ample for most uses. The method is to set 2 at B and the central slider at A, and to record the meter deflection as the desired balance reading. Then with the central slider still at A, 2 is moved to D and the bridge impedances are varied until the balance reading is reproduced. Then $I_1Z_1 = I_2Z_2$. The drops across Z_3 and Z_4 are then balanced in a similar manner with 1 at C. This may upset the first balance, but after a series of readjustments the whole bridge is finally balanced.

The effect of input capacitance in the tubes is minimized because there is a highly negative bias on the grids and the external load is small. The circuit can easily be built into a small portable instrument. Some idea of its sensitivity can be gained from the fact that it can differentiate between type 133K and type 102J General Radio resistors both rated at 10,000 ohms.

Voltage Relay.—A method[1] of employing the unbalanced voltage of a bridge circuit to operate a small unbalanced contactor to fulfill any prescribed control function has been described.

[1] GRAFF, J. W., An Electronic Voltage Relay, *Electronics*, March, 1934. See also LEWIS, *Proc. Phys. Soc. London*, vol. 34, p. 17, 1921; and SPENCER, *Instruments*, vol. 6, No. 5, p. 93, May, 1933.

Two arms of the bridge are resistor materials of a very low temperature coefficient. Two other arms are tungsten lamps, operated at a voltage at which their resistance is sensitive to voltage changes, that is, about one-quarter their normal voltage.
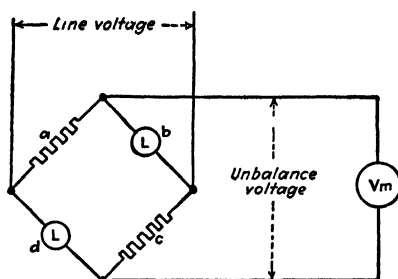
Fig. 57.—Bridge made of lamps and resistances responsive to voltage changes.

For ½ volt sensitivity the voltage impressed on the amplifier is about ⅙ volt, at 110 volts across the bridge. The circuit is shown in Fig. 57. The plates of the tubes are fed from an a.c. source acting as half-wave rectifiers. This gives the amplifier circuit a polarity-discriminating property since it will respond only to grid voltages in phase with the plate supply. Since an unbalance caused by high voltage has the reverse polarity of an unbalance caused by low voltage, the bridge discriminates between high and low voltage. Both tubes are biased to cut-off.
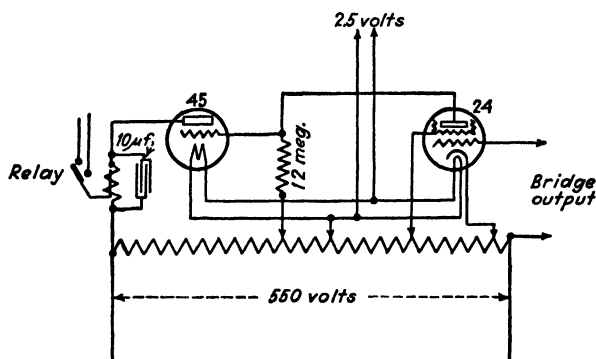
Fig. 57A.—Amplifier used with lamp-resistance bridge.

At the most sensitive adjustment, the grid bias of the first tube is the sum of a fixed grid bias plus the input from the bridge. Thus the bridge circuit can be made to operate along the steep portion of its curve. The output of the 45-tube is ample to

operate a relay such as the GE type HG.   Reliable relay operation is obtained with sensitivities down to 0.25 volt.   It can be arranged to operate from a current indication and is useful in automatic control operations such as sensitive over- or under-voltage protection or accurate current control.

Vacuum-tube Time-delay Relays.[1]—The application of the condenser charged or discharged through a resistor to close a relay, or perform other functions after a definite time interval, has been applied often. The condenser may be used in the grid circuit of a vacuum tube and not required to handle any amount of power, the relay itself being operated by the plate current of the tube. Of the many circuits, a few are discussed below.

In Fig. 58 is a simple d.c.

Fig. 57*B*.—Characteristic of circuit of Fig. 57.

circuit in which plate potential is obtained by the drop across one resistor, the drop across the other resistor keeping the
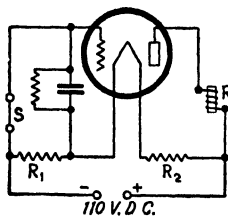
Fig. 58.—Simple d.c. relay.   Fig. 59.—Tube lit only when needed.   Fig 60.—Utilizing full line voltage.
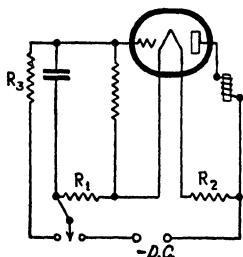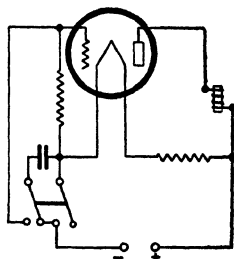
grid highly negative so long as the switch is closed.   When the switch is opened, the condenser discharges, more or less slowly, through its shunting resistor.   This lowers the negative

[1] Muehter, M. W., *Electronics*, December, 1933.

potential on the grid, and at a critical value the plate current of the tube will rise to a value sufficient to operate the relay.

The time of delay in Fig. 58 is about 3 sec. per microfarad per megohm at 110 volts.

In Fig. 59 the tube need not be lighted all the time. When the switch is thrown to the right, or operate condition, the tube lights up, the condenser charges through the grid resistor, the grid potential decreases until the relay operates. R_3 limits arcing when the switch is restored to normal, or nonoperate, condition.

In both of the above described circuits, the voltage available for the condenser is low; most of the voltage is taken by the plate

FIG. 61.—Circuit for   FIG. 62.—Fixed-impulse   FIG. 63.—Interrupter
maintaining operation.   relay.   circuit.
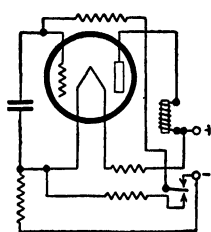
of the tube. In Fig. 60 the full line voltage may be impressed on the condenser, thereby prolonging the delay.

These circuits can be adapted to a.c. operation by providing a rectifier to furnish the d.c. In place of the rectifier a glow tube may be used. This requires no filament current.

In Fig. 61 is a circuit for maintaining operation for a certain ʼpredetermined time after the starting impulse has stopped. It requires a relay with a double winding. When the switch is operated the filament gets current in series with relay winding R_1. The relay pulls up and locks in the circuit through its own current. The second contact of the starting switch or button charges the condenser negative so that no plate current flows. When the button is released, the relay stays closed until the condenser discharges. Then plate current flows through the second relay winding, opposing the first winding and releases the armature restoring the circuit to normal.

Fixed-impulse Relay.—An impulse of fixed duration regardless of the length of the initial impulse may be obtained from **Fig. 62.**

When the switch is operated, the relay pulls up through one winding and locks. When the condenser is charged, the second winding energizes causing the relay to drop back. If the switch is still closed, nothing happens, for the condenser is charged. Releasing the switch permits the condenser to discharge and restores the circuit to its original condition.

Interrupter.—In Fig. 63 is an interrupter depending upon the previous circuits. At the start, the grid has zero potential, the relay pulls up transferring the condenser circuit to the charging position. The plate current now falls until the relay
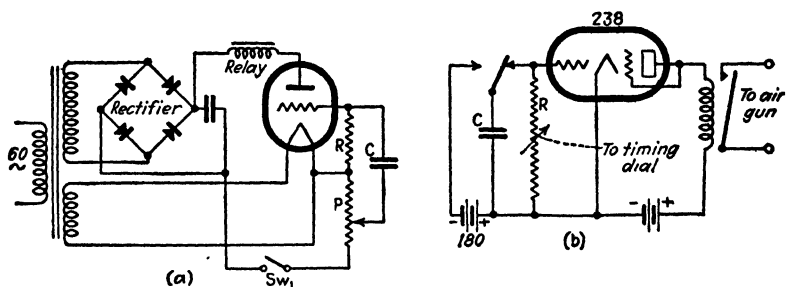
FIG. 64.—Time-delay relays; the second is used to control cathode spraying in tube manufacture.

releases, causing the condenser to discharge through the back contacts of the relay. Then the relay picks up and the cycle is repeated.[1]

Westinghouse Electronic Time-delay Relay.—This device has the advantages of lack of temperature error, has simplicity, instantaneous reset, wide range of delay, convenience of adjustment, and cheapness, a combination of advantages which no electromechanical-type relay possesses.

When initiating contacts (Sw_1, Fig. 64a) close, plate voltage is applied to the tube and it starts passing current. As the current increases, an increasing IR drop from potentiometer P is applied to condenser C through R. This increasing voltage causes a charging current through the condenser, and the IR drop across R due to this charging current applies a negative bias to the grid. Plate current through the tube, therefore, cannot build up very rapidly, because the faster it increases,

[1] For other tube-type time-delay relays see FELSTEAD, CHARLES, *Electronics*, March, 1936, p. 38.

the more negative the grid becomes. After a predetermined time which is adjustable by potentiometer P, the plate current will be sufficient to operate the relay. This relay then performs the operation which it was desired to delay until a certain interval after Sw_1 had closed.

The maximum time delay obtainable is proportional to the product of R and C. Thus when a range of long delays is desired, a large resistor should be used; for short-delays, a small resistor is used for the sake of sensitivity in the potentiometer control. Resistor R being a grid-leak type, these changes are easily made. The maximum delay which the device is capable of providing is 3 min., the minimum about 0.05 sec. Once the potentiometer has been set, the delay remains constant within 5 per cent.

Cathode-coating Circuit.—An automatic timer[1] (Fig. 64b) has been used in the manufacture of cathodes for thermionic tubes. The cathode coating must be under close control, the coating weight being dependent upon the time an air gun operates. The circuit makes it possible to preset the coating process for any time between 2 and 20 sec. by setting the dials properly when the air gun is automatically turned off at the proper interval.

Electromagnetic Balance for Force Measurement.—A device for measuring the aerodynamic forces acting on wind-tunnel models has been developed[2] which uses amplifier tubes and which may be applied to the measurement of other forces or to the maintenance of a constant current or voltage in an electrical circuit. It consists of a beam balance equipped with an electromagnet for the purpose of balancing the beam. The force maintaining the beam in equilibrium is provided by an automatic current control which adjusts the current in the electromagnet to counteract any tendency of the beam to tip in either direction.

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[1] KOECHEL, W. P., *Electronics*, May, 1933.

See *Electronics*, August, 1936, for Noble's method of timing photographic enlarger exposures by a tube circuit.

[2] EASTMAN, F. S., *Bull.* 60, Engineering Experimental Station, University of Washington. See also AINSLIE, D S , An Electromagnetic Balance, *Rev. Sci. Instruments*, October, 1933. On the use of a saturated two-element tube, a glow discharge, and an oscillograph for measuring air velocity in aerodynamical research, see LINDVAL, FREDERICK C., A Glow Discharge Anemometer, *Elec. Eng.*, July, 1934, p. 1068.

The magnitude of the current flowing in the electromagnet becomes a measure of the unknown force.

The simplest form of the circuit is given in Fig. 65. An "actuating coil" carried by the beam moves in a field provided by permanent magnets. Since this field is constant the force which the device will exert on the beam will be directly proportional to the current flowing in this coil. If this current is automatically kept at such a value as will balance the beam a current meter in series with the coil can be calibrated in any unit of force.
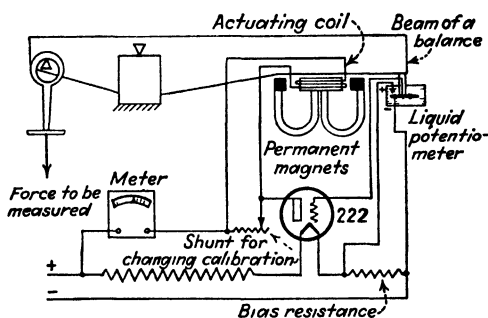
Fɪɢ. 65.—Electronic balance for measuring forces.

An electrode attached to the beam dips into a liquid potentiometer and is connected to the grid of an amplifier. Two fixed electrodes between which the movable electrode moves are connected to proper bias voltages so that when the beam tips in one direction, the bias of the tube is changed producing more (or less) plate current which flowing through the actuating coil tends to bring the beam back to its normal balance condition.

In practice the permanent magnet is done away with in favor of electromagnets; the liquid potentiometer is replaced by a transformer with two secondaries connected in opposition to each other so that when the flux divides equally there will be no voltage across the entire secondary winding. If, however, more than half the fluxes pass through one leg of the core, the secondary voltages will not be equal and this voltage difference can be amplified and used to control the balance of the arm as usual. The amplifier is a screen-grid tube biased to cut-off so that variations of the grid voltage due to the nonuniform distribution

of flux in the transformer will produce a change in plate current which is used to vary the bias of a pentode (47).

A variation in position of the balance beam of $\frac{1}{16}$ in. produces a change of from zero to 40 ma. in the pentode plate current.

The instrument will measure forces to within 150 g. with an error of less than 1 per cent; it will measure forces as small as 10 mg. Greater forces can be measured by using grid-controlled rectifiers producing greater electromagnetic forces.

The device, modified, of course, to fit the case, can be used to maintain a voltage or current constant with high precision. Since the meter deflection is proportional to the square root of the force, the instrument can be used to measure fluid velocity by balancing the impact pressure of the fluid by the electromagnetic current.
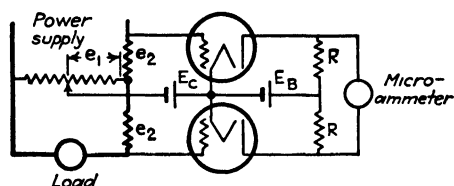
FIG. 66 —Circuit for measuring power.

The author points out that by using a light-sensitive cell instead of the magnetic control, forces of exceedingly small value could be measured.

Electron-tube Wattmeter.—The balanced or push-pull modulator has been used as an electron-tube wattmeter for the measurement of small power.[1] The circuit for this instrument is given in Fig. 66. The device has the following advantages: high sensitivity without seriously modifying the circuit being measured, high accuracy, linear scale, range easily variable, and calibration independent of frequency.

The load current is measured by the drop across a small resistance in series with the line, the load voltage is measured by the drop across a high resistance across the line. The sum of instantaneous values of the two component voltages is impressed on the grid of one tube and their difference on that of the other. The function of the balanced modulator arrangement is to

[1] TURNER, H. M., and F. T. MCNAMARA, An Electron Tube Wattmeter, *Proc. Inst. Radio Eng.*, October, 1930; see also Patent 1,586,553, E. Peterson.

eliminate undesired components from the indicating instrument, usually a d.c. microammeter, which measures directly the power supplied to the load. The instrument has been used to measure powers of the order of 20 μw and can be used for smaller powers. Its sensitivity for 250-type tubes is $(0.03 \text{ volt})^2$ per microampere. Thus, if 10 volts were applied to the load, a series drop of 3 millivolts would be required.

Improvements on the fundamental circuit shown are given by the authors involving a phase shifting bridge which permits greater sensitivity and a linear scale.

Other more recent uses of the vacuum tube for measuring low values of power will be found in the bibliography below.

An interesting use[1] of a double-grid amplifier tube known as the Wunderlich tube for measuring power of the order of a few milli-
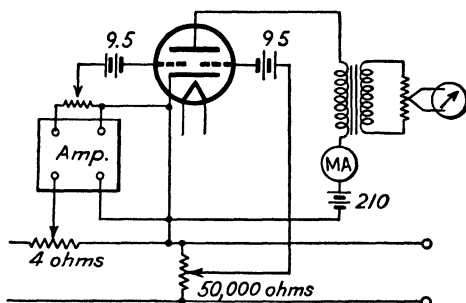
FIG. 66A.—Circuit of Wagner. (*Elec. Eng., December*, 1934.)

[1] WAGNER, TOM B., A Thermionic Tube Measuring Instrument, *Elec. Eng.*, December, 1934, p. 1621.

PIERCE, JOHN R., A Proposed Wattmeter Using Multi-electrode Tubes, *Proc. Inst. Radio Eng.*, April, 1936.

ALBERT, ARTHUR L., and HOWARD P. BECKENDORF, An Electrostatic Wattmeter, *Electronics*, March, 1936.

BARNES, G. W., A Vacuum Tube Wattmeter, thesis on file at Oregon State College, presented in May, 1930.

TURNER, H. M., and F. T. MCNAMARA, An Electron Tube Wattmeter and Voltmeter and a Phase Shifting Bridge, *Proc. Inst. Radio Eng.*, vol. 18, pp. 1743–1747, October, 1930.

ELDREDGE, K. R., A Wattmeter for Communication Circuits, *Elec. Eng.*, vol. 54, pp. 279–281, March, 1935.

WAGNER, T. B., A Thermionic Tube Measuring Instrument, *Elec. Eng.*, vol. 53, pp. 1621–1623, December, 1934.

BRADFORD, C. I., Radio-frequency Power Measurements with the Quadrant Electrometer, *Proc. Inst. Radio Eng.*, vol. 23, pp. 958–971, August, 1935.

watts as in communication circuits has been made by Wagner. This tube has two symmetrical and hence equally effective control grids. By impressing a voltage proportional to the current taken by a load on one grid and the voltage across the load on the other grid he has found that the device will not only operate as a wattmeter but can be used to give voltage, current, or power factor, thus supplying a means of measuring the four fundamental electrical quantities by one electron-tube instrument.

The circuit is given in Fig. 66*A*, and a calibration in the citation shows a linear curve from 3 mw. at 20 on the plate-current meter reading to 15 mw. at 100 deg. on the scale. The instrument had an error of approximately 2 per cent for frequencies between 100 and 3,000 cycles.

Measurements of Small Displacements.—An ingenious combination of vacuum-tube voltmeter and an Ames gage[1] makes possible the determination of the position of a physical object to within 25 millionths of an inch. The device was designed for measuring the deflections of the armature of a loud-speaker. Magnetic-type armatures (as distinguished from dynamic or moving-coil types) move approximately a thousandth inch per milliampere of armature current. It was desired to know if the armature moved the same amount on positive and negative half cycles of current. If it did not, distortion would result.

The Ames gage graduated in ten-thousandth-inch divisions was mounted in a suitable fixture over the speaker drive rod. In order that the pressure of the gage foot on the drive rod might not produce misleading results and to provide for fine control, a screw adjustment was added to the gage lever. The gage was insulated from the base by a wooden fixture supported on heavy metal brackets. A small piece of micarta provided insulation between the adjusting screw and the gage itself. In operation, readings were obtained by lowering the gage foot with the adjusting screw until contact with the drive rod was made. Binding post terminals, connected to the gage and to the metal base, were provided for a contact-indicating circuit.

A low-voltage lamp and battery were first tried as a means of indicating contact. It was soon found, however, that insufficient precision was obtained in this manner; the lamp would

[1] Glover, R. P., and T. A. Hunter, *Electronics*, January, 1931, p. 474.

glow over a range of about 0.002 in. The presence of contact resistance, therefore, ruled out any method which required an appreciable current to flow through the signal circuit.

The final circuit of Fig. 67 was obtained after some experimental work. A leak of 5 megohms resistance was connected across the input terminals of an electron-tube voltmeter and the deflectometer circuit was connected across the leak with a 1.5-volt battery in series. Thus, when the gage foot just touches the armature drive rod, the normal negative bias on the tube is
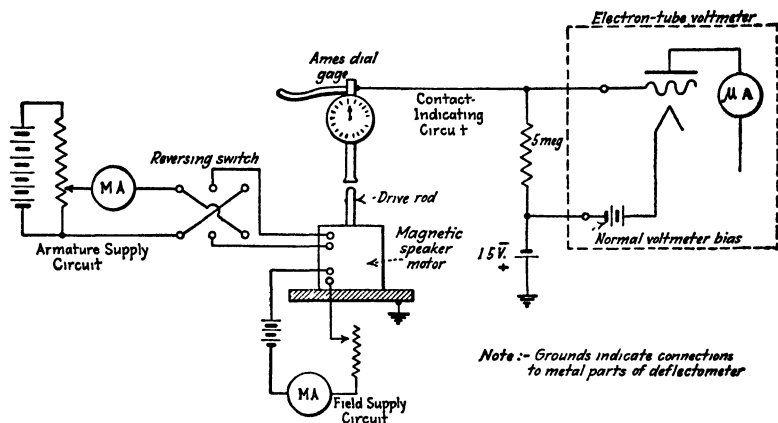
FIG. 67.—Circuit for measuring small displacements.

reduced by 1.5 volts, resulting in a sudden upswing of the microammeter pointer. In practice it was found that the position of the drive rod could be determined to within one-quarter dial division or within 0.000025 in. Further applications of this method will undoubtedly be found in the field of accurate measurements. (See also Chap. IV on tube micrometers.)

Measurement and Control of Humidity.—The circuit shown in Fig. 68 has been used by M. A. Marsh[1] for controlling humidity. It will be noted that the hair control closes either one of two tube circuits depending upon whether the room is to be humidified or lowered in percentage saturation. The apparatus will maintain humidity to within $\pm\frac{1}{2}$ per cent. The author states that the hair control might carry a mirror and reflect a beam of light to one of two phototubes and thereby perform the same function the relay does in the present circuit.

[1] *J. Sci. Instruments*, May, 1932.

International Shoe Company, St. Louis, uses a phototube and relay to control the humidity at a maximum value without condensation of moisture on the material in process. The phototube and light source are mounted outside the room on opposite walls. A relay operates a solenoid valve controlling the water supply to atomizers which pass the moisture into the air of the room.

Combustion Control.—A high-vacuum tube application to oil furnaces has been made by the Minneapolis-Honeywell Regulator
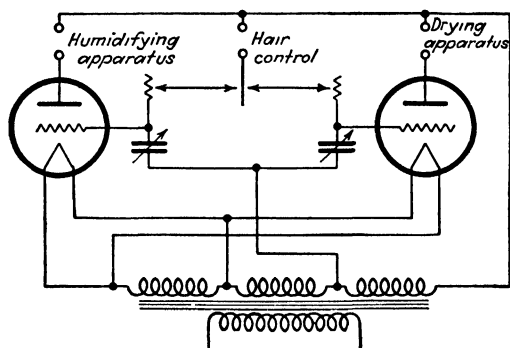
Fig. 68.—Humidity control circuit.

Company to replace earlier systems using grid-controlled rectifiers. In the new systems the flame circuit controls the grid of a high-vacuum triode so that the grid is positive when the flame appears, and a relay in the plate circuit of the tube operates. Since the flame circuit is connected to a tube energized from direct current (supplied by a rectifier) any capacity effects between the flame leads of electrode and ground do not affect the operation of the system. In earlier systems the conductivity of the flame was used to drain the electrostatic charge from the control grid of the tube. The grid connection, therefore was not an a.c. circuit, because it rectified current flowing through it when conducting and as a consequence was subject to capacity effects. In the new system the tubes and relays may be located at any desired point from the furnace. An interlock relay is used to prevent starting until both tubes and flame-responsive relay are in proper operating condition. Closure of the power relay is prevented until the flame circuit has been checked. The safety of the system is not dependent upon the relative speed

of the several relays. Another advantage is secured by slow charging of a condenser so that the ignition leads for the pilot flame may be delayed in cut-off after the pilot flame has been established to make sure of ignition.

It is worth noting that the designers of this equipment have used an 85-type tube, perhaps the earliest industrial usage of one of the combined tubes, in this case a diode-triode.

Measurement of pH.—Leeds and Northrup have designed a portable potentiometer-electrometer useful for measuring hydrogen-ion concentration and oxidation-reduction potentials. It may be used with a variety of electrodes and contains an amplifier tube DRH-507 which makes it possible to use a built-in compact galvanometer instead of the separate laboratory electrometer with light and scale formerly necessary for use with glass electrodes. The range of the device is 0 to 1,100 millivolts, and the limit of error is 0.2 per cent of the range equivalent to 0.03 pH approximately. With a Leeds and Northrup glass electrode a change of 0.03 pH in the solution results in a galvanometer deflection of at least 1 mm.

The Electronic Recorder.—A good example of the use of an amplifier in increasing the sensitivity of measuring instruments is the Westinghouse electronic recorder.[1] The comparatively low sensitivity of most recording instruments is due to the fact that the friction between recording pen and paper is from 100 to 1,000 times as great as the friction in a jewelled movement bearing. To prevent loss of sensitivity, therefore, some sort of relay is obviously needed between the measuring instrument and the recorder.

Several mechanical relays have been used in the past for this purpose, but they all had definite limitations in speed and sensitivity. To avoid these difficulties, Westinghouse has developed a new recorder which places a negligible load on the indicator. To use it, a small pilot coil, which may be seen in the lower pilot element in Fig. 69, is mounted on the moving part of the measuring instrument, the primary element, and is suspended in the alternating field of an electromagnet. Its function is to follow the motion of the measuring element.

A second, duplicate, pilot coil is mounted on the recording mechanism and is suspended in an alternating field which is

[1] BERNARDE, H. L., and L. J. LUNAS, *Elec. Eng.*, March, 1933.

energized by the same source as the field for the first coil. The two coils are connected in series-opposing. The voltage difference (about 50 millivolts per degree deflection) is amplified and applied to one phase of the pen-driving motor which is a two-phase induction motor. The other phase is fed by the same source which supplies the fields in which the two pilot coils are suspended.
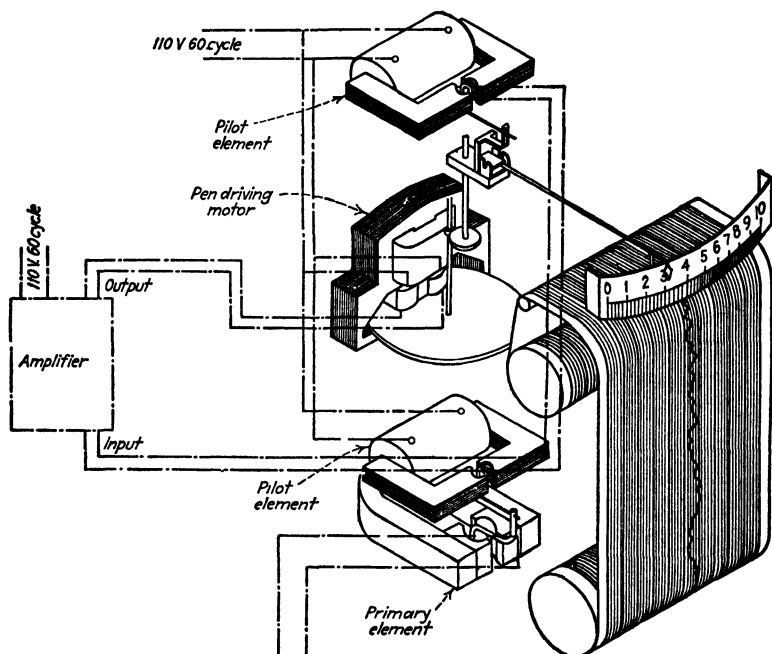

FIG. 69.—Circuit for increasing sensitivity of recording instrument.

With this arrangement, the voltage supplied to the motor from the coils depends on the algebraic sum of the e.m.fs. induced by them, which, in turn, depends on the difference in their deflections. Also, the polarity of the deflection difference determines whether this voltage is in phase with the other voltage supplied to the motor or is 180 deg. out of phase with it. Therefore, since the motor rotates the second pilot coil, it will always keep that coil in the same orientation as the first one. At the same time, the pen records the position of the second coil and so draws the desired curve.

This instrument has the usual advantages of a null method in that it is free from errors due to stray fields, variations in line voltage, etc., because both coils are equally affected by these disturbances. Variations in amplifier-tube characteristics have but an unnoticeable effect on speed of response. Furthermore, since the motor speed is proportional to differences in position of the two coils, it can be made to move as fast as desired without fear of hunting.

The instrument will record d.c. millivolts and microamperes at energy levels of 4 or 5 μw. A D'Arsonval mechanism in combination with a Rectox rectifier makes possible the recording of alternating currents with a full-scale value as low as 200 μa. Alternating voltages can be recorded in the same manner with a full-scale value of 1 volt by using a potential circuit resistance of 5,000 ohms per volt.

This recorder should find innumerable applications in the recording of such feeble quantities as thermal e.m.fs., vacuum-tube currents, photo-electric currents, and for automatic recording of light intensities and magnetic-strain gage readings whose deflections represent deformations of the order of thousandths of an inch. Narrow-range (*e.g.*, 59 to 61 cycles) frequency indications or any alternating or direct current of lower energy than it is possible to record by conventional means may be recorded. With such a device high-speed, long-distance telemetering or follow-up mechanisms (such as anti-aircraft gun pointing) is distinctly possible. A photo-electric recording mechanism for performing almost or exactly the same function will be found in the proper chapter.

Amplifier-controlled Potentiometer Pyrometer.—Bailey Meter Company has developed a potentiometer pyrometer, named "Galvatron" after the galvanometer-electronic relay circuit which it employs, to operate slide-wire resistances and recording pens. The instrument may also be used as a resistance thermometer, a smoke recorder, or a telemetering system.

One Galvatron may include as many as four potentiometer circuits, the contact-making galvanometer being automatically switched from one circuit to the next by relays actuated from contacts made by a synchronous-motor-driven time device. One synchronous motor drives these timing contacts for the relay as well as for the galvanometer-contacting mechanism,

the recording chart, and the automatic standardizing relay contacts.

The mechanism of the instrument consists of a galvanometer of short period arranged to make contacts of a duration proportional to the deflection of the galvanometer needle from neutral.   These contacts which close the circuit to the electronic relay carry only a few microamperes of current and are connected to the grids of amplifier tubes.   A galvanometer contact permits the flow of direct current through one tube and the d.c. winding of its transformer whose second winding is in series with one field coil of a reversible synchronous motor driving the potentiometer unit.   This flow of direct current permits a flow of alternating current through the transformer and field coil, thereby rotating the motor in one direction.   Rotation in the opposite direction is produced in the same manner by energizing the other field coil through a second electronic relay when the galvanometer needle swings to the other side of neutral.

Split-second operation of the reversing synchronous motors is obtained by the use of the Galvatron circuit, since the electronic relays act instantaneously in accordance with the galvanometer contacts.

Because of the very small current flow required to operate the electronic relay, it is possible to use light pressures on the galvanometer-contacting mechanism without danger of burning. No failures to make contacts are experienced because of an increase in the resistance caused by collection of dirt or oxide at the contact points.   A further advantage gained by the use of light contact pressure is the reduction of strain on the galvanometer needle and suspension ribbons.   This permits the reduction of weight of the galvanometer needle, thereby decreasing the operating period of the galvanometer and improving the speed of operation.

Automatic standardization takes place approximately every four hours at which time the dry cell is balanced against a standard cell.   Contacts from the galvanometer, properly amplified through the electronic relays, effect this balance by the adjustment of a motor-driven resistance in series with the dry cell.   A small indicator, visible from the outside of the hinged panel on which the mechanism is mounted, shows the condition of the dry cell by a series of numbers, each successive

number indicating that the dry cell is more nearly exhausted until a red signal indicates that the cell should be replaced.

A continuous record, or records up to four in number, is made on a circular recording chart. When more than one record is provided for, each is made in a different color of ink so that it can be distinguished from the others on the chart, regardless of how many times they cross each other. In the case of a multi-pen recorder, all records are continuous, although the contacts made by the galvanometer needle are divided among the potentiometers. In the case of a one-pen recorder, all contacts made by the galvanometer serve to adjust the potentiometer, which in this case is adjusted every 4 sec. if necessary. In the case of a four-pen recorder, each potentiometer receives a contact every 16 sec., so that each record is a smooth continuous picture of existing conditions.

Measurements of Weak Alternating-current Fields.—By means of interchangeable coils of various sizes and numbers of turns coupled to a vacuum-tube voltmeter, G. Lubszynski of the High Tension Laboratory, Berlin Institute of Technology, has explored weak magnetic fields of the order of 10^{-5} gauss, the upper limit with a 2-ma. meter being 400 gauss. The frequency range was from 10 cycles to 300 kc. The a.c. field in the vicinity of a 50,000-kw. generator was explored, the fields being 2.5 gauss at 1-m., 0.1 gauss at 4.5-m. distance.

The first tube to which the exploring coil was connected acted as a detector and was direct coupled to a following tube acting as a d.c. amplifier.

A somewhat similar use has been made of amplifier tubes in the detection of metallic objects, and in traffic control. For example, a door through which employees of a plant must pass on leaving their work may be equipped with coils through which alternating current passes. If the employee has metal in his pockets for which the system has not been compensated, a plate-current meter will indicate its presence. The principle is simply that the metallic object absorbs energy from the field through which the employee passes. This absorption of energy changes the plate current of an amplifier tube and this change may be indicated on a current meter.

The detection of concealed weapons by police has been accomplished by the same method. Here the suspect is brought near

a large exploring coil while a smaller coil is held at various positions with respect to the criminal to detect hidden metallic objects.

In traffic control an automobile, for example, may couple magnetically two coils placed at opposite sides of the roadway. This coupling may be made to operate the red signal on a cross road so that the control car may have a green light for passing.

The general method has been used for testing welded materials for flaws. If the weld has made the proper union the electrical resistance of the piece will be uniform. But, if the piece is moved through a field, a poor weld having a higher resistance than the remainder of the metal will cause a deflection in the current-measuring meter on the test equipment.

Metal Detectors.—In a system developed by RCA Victor engineers for detecting concealed weapons, etc., carried through a door by a person, three parallel loops are concealed in the framework of the doorway and connected to a control box. A flow of voltage set up in the center, or driver, loop is picked up by the two outside loops, spaced at equal distances apart to create a perfectly balanced circuit. The introduction of a metallic object such as a gun, files, or a knife will upset the delicate balance of the circuit and cause an alarm to be given. A feature of the device is that, through the use of a cathode-ray tube in the control unit, anyone may adjust the mechanism to the proper balance visually with a simple turn of a knob without any additional manipulation once it has been set (see also Chap. VII).

In the oil industry it is often necessary to find buried pipes for the purpose of reconditioning them or of removing old lines. A simple method has been that of using a spark coil transmitter, say a Western Electric No. 5 induction coil with vibrator with two probes or rods attached to fairly long wires. One rod is connected to the pipe; the other is driven into the ground. Electric waves travel along the pipe and through the ground and can be picked up in a simple detector-amplifier connected to a pair of headphones. The pipe line is then located by the use of an antenna wrapped on an 18-in. bicycle rim, a small amplifier, and a set of headphones. The operator walks down the pipe line guided by the tone heard in the headphones from the antenna, which is moved slowly from side to side of the pipe

line, the strongest tone being always directly above the pipe line.

The character of the soil and the condition of the pipe or coating create the most variables governing the distances to be used between transmitter settings. On well-coated pipe the transmitter can be heard over a distance of 7,000 to 8,000 ft., and on bare pipe the maximum is about 1,300 ft. Also, wet ground, clay, or salt marshes present a good return path for the currents, and the transmitter can be heard for only approximately ¼ mile, whereas dry sand or rocky soils will permit operations over a distance of a mile or more between settings.
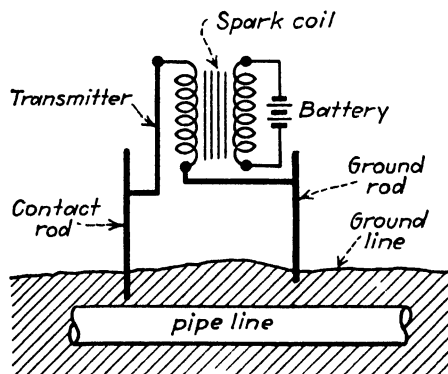
Fig. 70.—Circuit used for locating buried pipe lines.

Viscosity Tests by Vacuum Tube.—Many heavy viscous liquids are used in the manufacture of resistors used in radio receivers, and it is important that the viscosity of these be the same every time they are employed in order to maintain the uniformity of the finished product. A simple method[1] of checking the viscosity of such liquids is shown in Fig. 71.

A quantity of the liquid to be tested is placed in the inclined glass tube which is inserted as shown in Fig. 71 between two spaced coils in the grid circuit of the vacuum tube. A heavy steel ball is then rolled through the liquid in the glass tube and when this ball passes through the two coils it causes two successive clicks which may be heard in the headphones or two flickers of the plate milliammeter. The time required for the ball to roll the distance D through the liquid in the tube at a

[1] PODOLSKY, LEON, *Electronics*, July, 1933.

given angle and at a certain temperature is a measure of the viscosity of the liquid. For direct comparison of different samples of the same liquid it is only necessary to note the time between the two flickers of the plate milliammeter, or the two clicks in the phones, with a stop watch for a standard liquid of
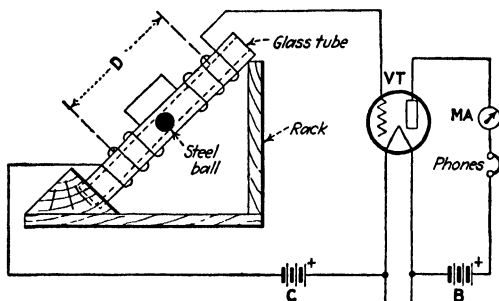
Fig. 71.—Viscosity measuring circuit.

the proper viscosity, at a given temperature, and to compare this time with that obtained for other samples, a longer time indicating higher viscosity and vice versa.

Automatic Testing and Rejection of Resistors.—A method[1] which is used in production testing resistors, such as are widely
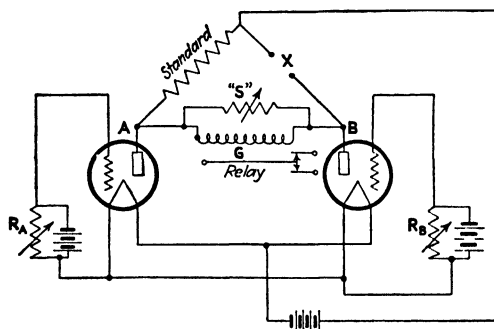
Fig. 72.—Bridge circuit which automatically tests resistors in manufacture.

used in radio receivers and other electronic apparatus employing amplifier tubes, is shown in Fig. 72. It is a bridge circuit, two arms of which are vacuum tubes, the other two arms being a standard resistor and the unit to be tested. A standard resistance of the desired value is placed in the plate circuit of tube *A*

[1] PODOLSKY, LEON, *Electronics*, July, 1933.

in the position marked "Standard," and another resistance of the same value in the X position in the plate circuit of tube B. The grid biases of the tubes are then adjusted by means of the potentiometers R, so that the plate currents of the tubes are equal. Then the voltage difference between the plates of the tubes will be zero and the galvanometer relay will be in the neutral position. Now if the standard placed at X is removed and a mechanical system brings the resistors to be tested successively to this position, the plate current of tube B will be dependent upon the resistance value of X. Consequently a voltage difference will appear across the plates of the two tubes if X varies from the value of the standard, the magnitude of the voltage being dependent on the degree of the variation. The polarity of this voltage difference will be dependent upon whether X is higher or lower in resistance value than the standard and consequently the direction in which the galvanometer relay G is closed depends on whether X is higher or lower than the standard. The contacts of the galvanometer relay are connected to suitable circuits for operation of the mechanical ejecting apparatus which separates the resistance into groups. The amount by which the X units may vary from the standard in either direction without being ejected is controlled by the shunt S across the relay, this shunt being adjusted to allow a proper current to close the relay. A multiplicity of such tube bridge circuits are usually mounted in conjunction with a single conveyor system.

Measurement of Time Intervals.—In the manufacture of vacuum tubes it is often important to know the exact length of time it takes the heater or filament to come to its normal operating temperature. The usual method is to utilize a stop watch and note the time between inserting the tube in the socket and the time required for the plate current to reach a predetermined value.

The circuit[1] in Fig. 73 permits quick and accurate determination of heating time regardless of type of tube or exact value of plate current. Of course, the circuit can be used for measuring other time intervals.

The elapsed heating time is registered and recorded by a telechron clock. Insertion of the tube in the socket starts the

[1] KOEHCHEL, W. P., *Electronics*, September, 1932.

clock. As soon as the cathode of the tube has reached its maximum temperature, the clock stops running. The elapsed travel time of the second hand represents the exact heating time of the tube. The minute hand is used as a zero indicator in order to have a means of knowing the starting time when the tube was inserted.

The underlying principle of this circuit is as follows: A one-stage amplifier is so connected that it will be acted upon only by a change in plate current of the tube under test. When
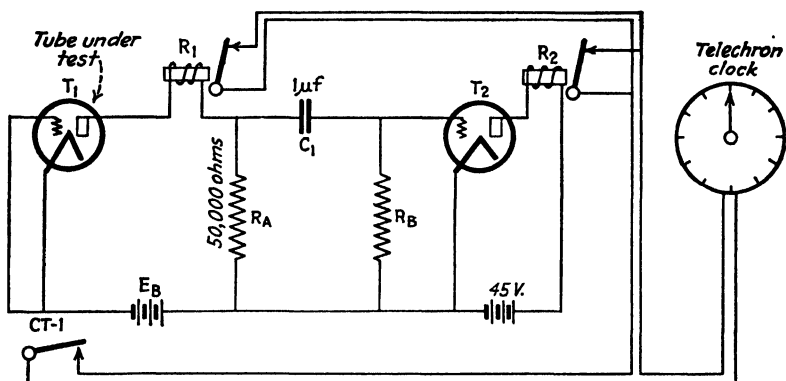
Fig. 73.—Method of measuring time required for tube filament to heat.

there is no further change in filament temperature (and consequently no further change in plate current), the amplifier is no longer acted upon and then operates indirectly to shut off the telechron clock.

Detailed circuit operation follows:

Contacts CT_1 are closed by physical contact due to insertion of the tube in the socket. As there is no plate current flowing when the tube is first inserted, relay R_1 will, therefore, be in an inoperative position. Therefore, its contacts will be closed. These contacts being in series with the contacts CT_1, the circuit is completed to the telechron clock. Relay R_2 is meanwhile in an operative position due to plate current through it of tube T_2 (as at this time there is zero bias on the grid of this tube, it will have its maximum plate-current flow). However, as soon as plate current starts to flow in T_1, there will be a voltage developed across R_A, and this in turn will permit charging current to flow through condenser C_1 and resistance R_B. This charging

current acts as a negative bias on the grid of tube T_2 and soon becomes sufficient to cut down the plate current of tube T_2 and release the armature of relay R_2. After a certain interval the plate current of the tube under test increases sufficiently to operate relay R_1. However, as the contacts of this relay and those of R_2 are in parallel, the circuit of the telechron clock will still be complete, for the contacts of relay R_2 will remain closed until plate current again flows in tube T_2. This plate-current flow (through T_2) will not take place until current flow through C_1 and R_B has entirely subsided, which condition will be obtained

120 V D C supply

5,000 ohm relay

210 A

430 ohms

60 ohms

1,000,000 ohms

To heater or relay

Thermo-stat contacts
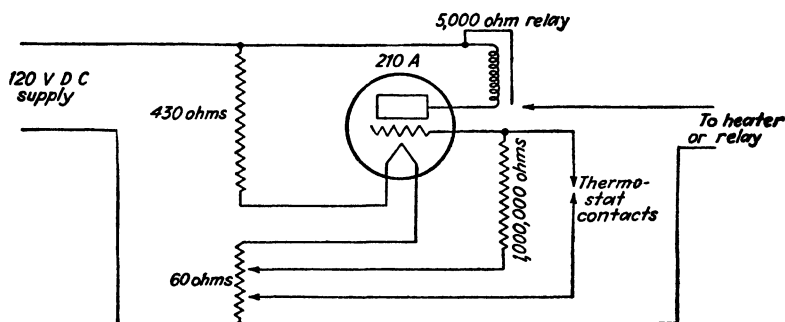
Fig. 74.—Simple temperature-control circuit; the tube removes heavy currents from thermostat contacts.

when the filament of tube T_1 reaches its maximum value. When the temperature (and consequently I_p) has its maximum value, current ceases to flow through C_1 and R_B thus allowing the grid of tube T_2 to again assume zero bias potential. This permits relay R_2 to operate and the contacts of this relay to open the circuit to the telechron clock.

Temperature Control.—A vacuum tube[1] and a bimetallic strip used for controlling the temperature of small oil and air baths are shown in Fig. 74. The tube reduces the current that must be handled by the thermostat so that a very slight movement of the latter is sufficient to operate the control. This circuit will control the temperature to better than 0.1°C. if a high-resistance relay is used. The potentiometer permits operation without batteries provided, of course, a source of 120 volts d.c. is available.

[1] SHARP, C. H., *Electronics*, September, 1932.

Other methods of using electron tubes for temperature control will be found in the chapters on light-sensitive apparatus and controlled rectifiers.

Field for Electron-tube Control for Rotating Machinery.—Inertia and friction in the moving parts of mechanical-type voltage regulators place a definite limit on their sensitivity and speed of response to voltage variations. In most industrial applications, speed of response is considered unimportant unless there are lights in the circuit, but there are cases, in motion
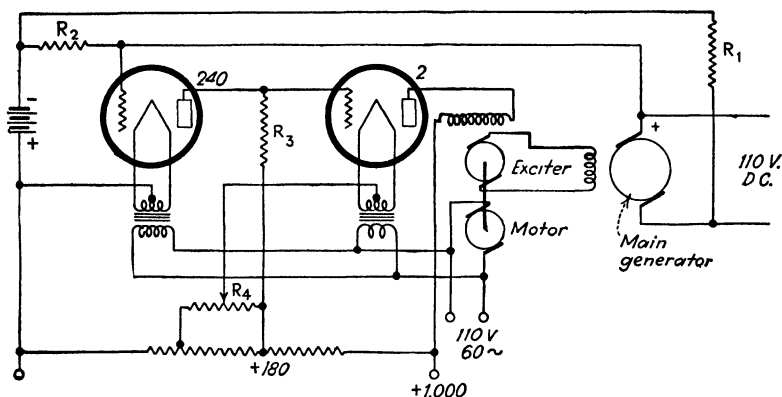
Fig. 75.—Voltage regulator circuit for d.c. machine.

picture studios, for instance, where speed is very much to be desired. Mechanical-type regulators are therefore not completely satisfactory.

Voltage Regulation.—Various schemes have been suggested for using electron tubes to control the output or speed of rotating machinery. One of the circuits[1] to be described for general application to d.c. machines is shown in Fig. 75. It employs a high-mu tube coupled directly to a power tube (d.c. amplifier) whose output current passes through the field of the exciter generator supplying the main generator field. Batteries balance

[1] VERMAN, L. C., and H. J. REICH, *Proc. Inst. Radio Eng.*, vol. 17, No. 11,2075, 1929. See also VAN DER BIJL, pp. 271–373; WOLD, P. I., and O. E. BUCKLEY, U. S. Patent 1,434,869; CRAFT, E. B., and E. H. COLPITTS, *Trans. Am. Inst. Elec. Eng.*, vol. 38, Part 1, 330, 1919; KING, R. W., *Bell System Tech. J.*, vol. 2, No. 4, pp. 96–98, 1928; STOLLER, H. M., and J. R. POWER, *J. Am. Inst. Elec. Eng.*, vol. 48, No. 2, p. 110, 1929; VERMAN, L. C., and L. A. RICHARDS, *Rev. Sci. Instruments*, October, 1930, p. 581.

out most of the line voltage (110) in the grid circuit of the first tube.

The field of the generator was designed so that its resistance matched the plate resistance of the power tube and operated well below the knee of the saturation curve for the exciter in order to get maximum change in the output for given change in the line voltage.

When the line voltage decreases, the negative bias on the 240 increases, thereby decreasing its plate current, lowering the drop across the resistor coupling the first and second tubes, and increasing the current in the plate circuit of the second tube. This boosts the exciter voltage and hence the line voltage. The device proved satisfactory on a 25-kw., 110-volt machine. This circuit is shown merely to illustrate one method of voltage control by vacuum tubes. The scheme is special in that the exciter field is excited from 1,000 volts direct current which makes it a special machine. Because of the inductance of the generator and exciter fields, means must be provided to prevent hunting as shown in other methods of control described later in this book.

D.C. Voltage Regulator.[1]—A circuit used for maintaining voltage constant as required in testing incandescent lamps is shown in Fig. 76 representing Westinghouse equipment installed at the Electrical Testing Laboratories. A 90-volt B battery is connected to oppose the voltage between the adjustable arm of the potentiometer (5, 6) and the positive terminal of the common generator and potentiometer connection. Under normal conditions this voltage difference is of the order of 2 volts and is impressed upon the grid of the first DRJ-571 amplifier which, through a second tube, controls the six high-current, high-vacuum, RJ-563 tubes in parallel with the supply from the 400-volt exciter to the 20-kw. generator.

Since the regulator varied the generator field current directly, no antihunting means was necessary, this being required only if the regulator were supplying excitation to an exciter whose armature delivered the generator field current.

Assume that the generator load is increased with a drop in regulated voltage. The effect of this voltage drop is to decrease the negative bias on the grid of the first amplifier, with consequent

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[1] KILPATRICK, F. E., and CARL P. BERNHARDT, *Electronics*, November, 1934; see also voltage regulators in Chap. IV.

increase in tube-plate current. Owing to the resistance coupling between amplifier tubes 1 and 2, the plate current of the second tube will decrease, thus decreasing the negative bias or grid voltage applied to the RJ-563 tube. Since the field of the 20-kw. generator is connected in series with the plates of the RJ-563 tubes and the 400-volt supply, the field current is correspondingly
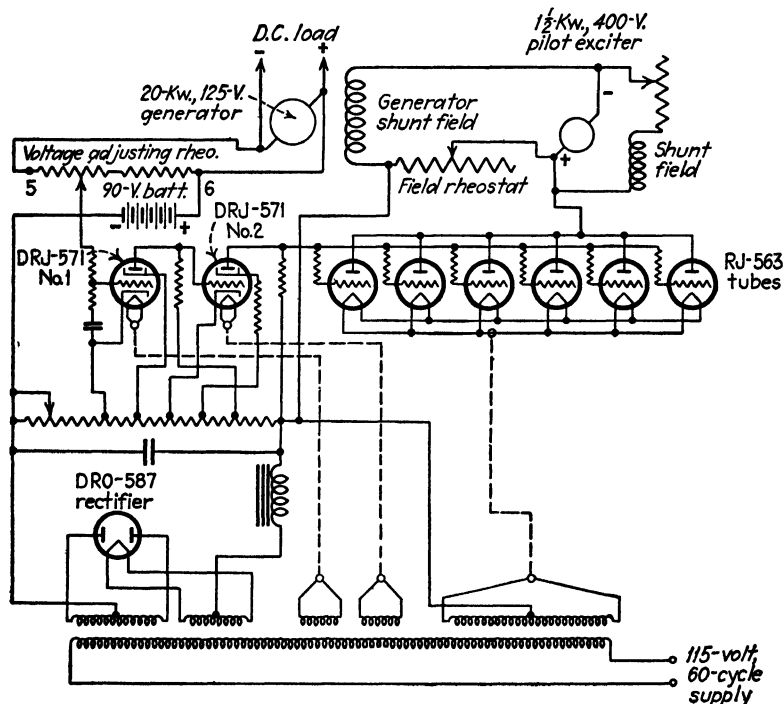
Fig. 76.—Direct-current voltage regulator.

increased with a resulting rise in generator voltage to normal. Under conditions where the regulated voltage increases momentarily owing to a change in load, the regulator action is exactly opposite to that just described.

The normal field current of this 20-kw. generator at the maximum load at which it will be used is 1.9 amp. Since the electronic voltage regulator is designed to deliver a maximum of 0.9 amp. field current, a manually controlled field rheostat was connected in parallel with the regulator as shown. Thus the generator field current is the sum of the current through the

manually controlled field rheostat circuit and the automatically varying regulator current.   This use of the field rheostat is desirable, since it permits reducing the field current which must be supplied by the RJ-563 tubes with a consequent increase of tube life.   Under normal conditions the tube-life expectancy is of the order of 2,500 hr. even in this exacting type of service.
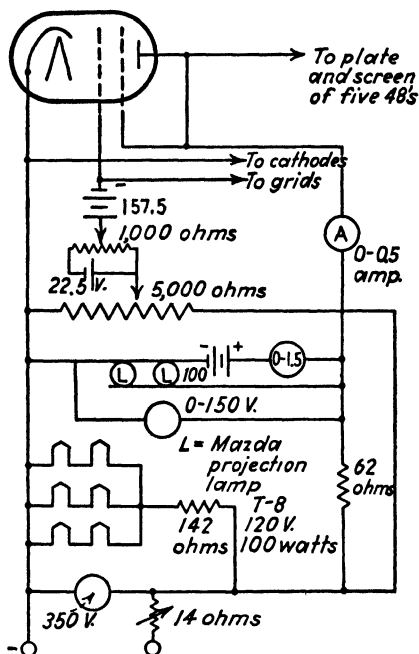
Fig. 77.—Light source voltage regulator.

Voltage Regulator for Constant Light Source.—A control unit described by Hughes and Hurka[1] offers a continuous regulation of about 1.7 amp. of direct current at a constant voltage of 100 volts (plus or minus 0.04 volt) over a total variation of plus or minus 7 volts on a 240-volt line.   The arrangement which employs six type-48 power-output tetrodes in parallel, characterized by extraordinary high transconductance (about 3,800 micromhos), is adaptable to circuits with other constants and has proved stable, showing no variation in 3- or 4-hr. runs.

[1] HUGHES, HAROLD K., and RUDOLPH J. HURKA, *Rev. Sci. Instruments,* September, 1935, p. 289.

In operation an increase in line voltage decreasing the grid bias allows the increase in current to flow through the tubes rather than through the lamps. Slight variations in the transconductance prevent perfect compensation.

Regulation by Means of Carbon Pile.—The Safety Car Heating and Lighting Company has devised a method of regulating the voltage of an alternator within 1 per cent using a carbon pile.
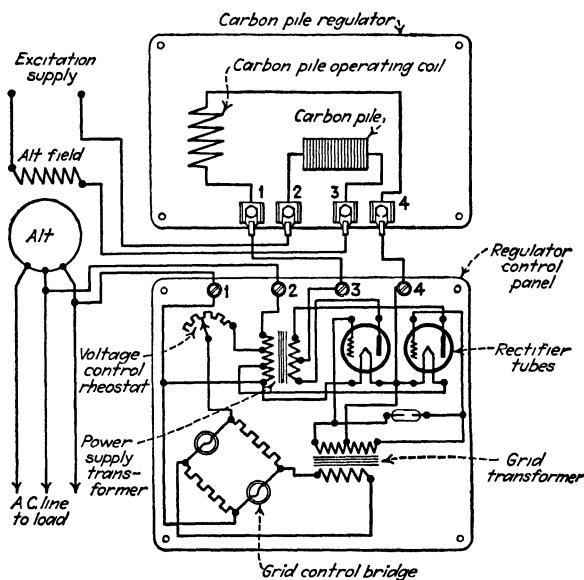
FIG. 78.—Carbon-pile voltage regulator actuated by thermionic tubes.

The alternator voltage is changed to direct current by a grid-controlled rectifier. Changes in alternator voltage modify the grid bias. The resulting amplified voltage changes are applied to a coil, which changes the pressure on a carbon pile in accordance with changes in impressed voltage and thereby changes the resistance in the generator field or exciter field. Similarly, the varying carbon-pile resistance can be used as a line resistance to control the current going to a load of some nature.

Train-control Equipment.—The following description of the amplifier and associated equipment installed on the Chicago and Northwestern Railway by the General Railway Signal Company applies to what is known as the continuous, inductive, single-phase, two-speed system. The object is to enforce safe train

speeds by imposing maximum, tapered, and low-speed limits which are continuously responsive to traffic and track conditions. The train is left in the hands of the engineman so long as he operates it safely, but in case of trouble, or in case the engineman fails to operate in accordance with the system, the automatic control applies the brakes to the train.

Alternating current at 60 cycles is introduced into the rails at the terminus of each block or tract circuit. It flows down one rail and through the locomotive axles to the other rail and then returns to the point of introduction. So long as alternating current is present in the rails, the locomotive apparatus indicates "proceed." When it is absent the apparatus displays a restrictive indication.

A portion of the magnetic field surrounding the rails, due to the alternating current in them, is picked up by coils carried on the pilot beam and which hang just ahead of the first pair of wheels. One coil is over each rail and about 6 in. above the rail. The 60-cycle voltage induced in these coils is amplified in a two-stage push-pull amplifier whose output operates a controlling relay. When current flows down only one rail, or both rails in parallel, this relay indicates "caution," but under normal conditions, the position of the relay will be such that the "proceed" signal is displayed.

In other systems the coils carried by the engine pick up signals as they pass inert roadside elements consisting of a laminated core wound with wire connected to the signal system through a relay. Depending upon the position of this relay, controlled by track or signal conditions, the pick-up system on the engine gets stop, caution, or proceed signals, or actually controls train speed.

In still other systems several currents of different frequencies are transmitted along the tracks, or a single frequency, 100 cycles, is interrupted at various rates (80, 120, 180 interruptions per minute) for approach, approach restricting, or clearing indications to the engineman.

Amplifiers are not necessarily used in these systems, although they usually are. The older method of making an actual mechanical contact between the train and some device along the track has given way to electrical methods, either d.c., a.c., or amplified a.c. methods.

Noise Measurement.[1]—The use of amplifier-voltmeters to measure all manner of industrial noises, sounds, or vibrations is an obvious application of amplifier tubes. The noise is picked up by a microphone whose currents are amplified sufficiently to
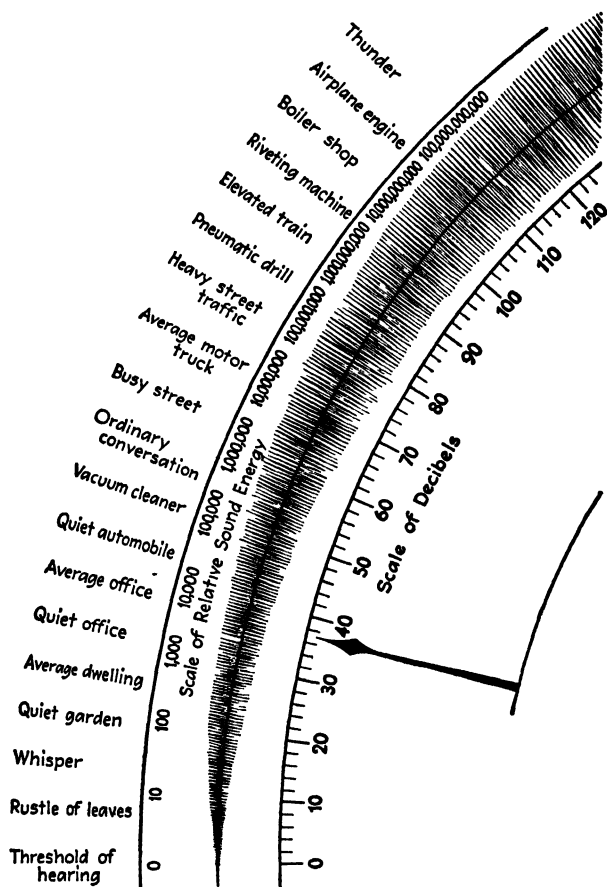
Fig. 79.—Range of sounds experienced in life. (*Electronics.*)

be read on a rectifier current meter (vacuum-tube voltmeter or copper oxide rectifier). Studies of subway or street noises, and vibrations of rotating machinery are but a few of the uses to which such devices have been put. In some cases a study of not only the quantity of noise but of its various frequency or

[1] See FREE, E. E., *Rev. Sci. Instruments*, July, 1933. JACKSON, J. A., Quiet Electrical Machinery, *Gen. Elec. Review*, September, 1933.

tone characteristics is made. Such a study involves amplifying the noise, and then measuring by means of selective filters, the noise existing within a narrow band. In this manner the predominant frequency characteristic may be determined and the power in various frequency bands may be measured.

Noise-measurement equipment is usually calibrated in a logarithmic unit called the "decibel." This unit may be expressed mathematically as shown below.

$$\text{Db.} = 10 \log_{10} \frac{P_1}{P_2}$$

Thus it is seen that a decibel is a logarithm of a ratio between two powers. The advantage of such a system lies in its compactness, the fact that the human ear "hears" logarithmically, that one decibel is about the lowest ratio between two sounds that the ear can distinguish, and the fact that in amplifier calculations addition and subtraction may be used instead of multiplication and division.

The table below gives the equivalent power ratios of several values of decibels. Zero level in sound measurements is taken as one ten-billionth microwatt of sound energy per square centimeter. The chart in Fig. 79 taken from *Electronics* gives an idea of the range of sound pressures expressed in decibels experienced in everyday life.

The amplifier in such equipment must be "flat," *i.e.*, responsive to all frequencies alike, or must be properly equalized to be flat so that the true character of the sounds to be analyzed may be determined. The final meter is usually a d.c. current meter which reads the rectified currents produced in the final tube or rectifier.

Power Ratio	Decibels
10	10
20	13
·100	20
500	27
1,000	30
10,000	40

Commercial Noise-measurement Equipment.—Apparatus of this general type has been put on the market by various commercial manufacturers. Others have developed noise meters

for their own use in making surveys of the acoustical properties of auditoriums, machinery, etc.

A good example of a noise meter is that made by the E. E. Free Laboratories (Type 123).   It is portable.   One reading of noise intensity can be made in one minute, repeated readings in a given location require less than 10 sec. each.   It has been used to measure noise in factories, offices, homes, hospitals, by salesmen selling noise-reducing materials, in inspection of fans, motors, refrigerators, airplane noise, etc.

The instrument is calibrated in decibels above a zero level of 10^{-16} watt of sound energy per square centimeter.   In air and under ordinary conditions of temperature and pressure, this is the equivalent of 0.207 millibar of sound pressure.   The intensity range is from 35 to 125 db. above this zero level.   The lower figure is about the noise of a quiet residence in the country; 120 db. is the noise produced by an unmuffled airplane engine 15 ft. from the ear.

Noise differences of 20 db. are read directly, intermediate steps are measured by means of a variable attenuator which is calibrated in 5-db. steps.   The indicating meter is damped to an average period of $\frac{1}{3}$ sec. so that rapidly varying noise changes can be read.   The instrument reads noise to an accuracy of within 2 db. and usually 1 db., over a frequency range from 200 to 3,500 cycles per second.

The device is really a high-gain, high-quality amplifier, flat in response from 100 to 8,000 cycles per second, equipped with a microphone, which may be disconnected or interchanged, and an output meter.   For the majority of practical usages, the readings in decibels correspond to the relative loudness as heard by the human ear.

To make an actual analysis of the various components of noise, these laboratories have a filter system which, connected between the microphone and the amplifier, divides the noise up into narrow discrete bands, so that the relative loudness of each component may be obtained.   Other sound-measuring amplifiers are also obtainable from the Free Laboratories, more complex and expensive than the portable device described here.

A schematic block diagram of the Burgess acoustimeter is given in Fig. 80.   A good example of the use of such noise-measuring equipment will be found in *Instruments*, December, 1932, where

W. F. Billingsley, test engineer for the B. F. Goodrich Rubber Company, describes tests made with the Burgess meter to determine the causes of noisiness in automobile tires. A Jenkins
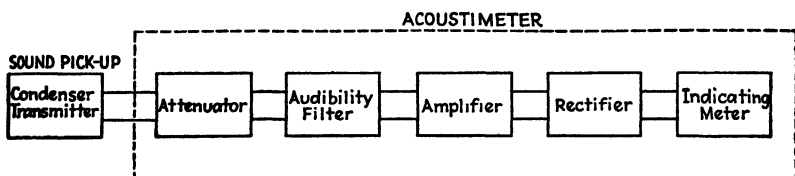
FIG. 80.—Block diagram of noise meter.
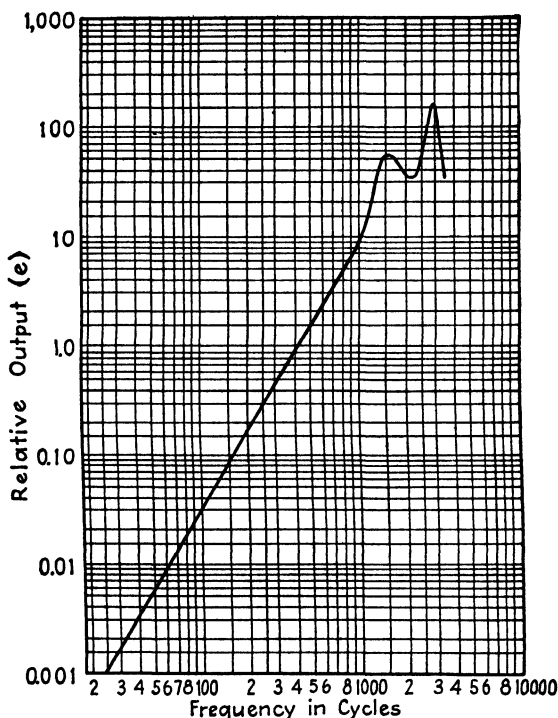
FIG. 81.—Characteristic of Rochelle salt vibration indicator. Constant amplitude of vibration of .001 in. Approximate resonance frequency is 2,950 cycles.

and Adair microphone sends the noise currents into the acoustimeter through a 1,000-cycle filter to cut out wind noises, etc., of high pitch.[1]

[1] See OPLINGER, K. A., An Electrical Ear, *Elec. J.*, August, 1931, which contains description of a Westinghouse noise-measuring instrument and an extended bibliography of articles on this general subject.

Vibration Pick-up Unit.—An interesting application of the property of piezo-electricity has been made by the Brush Development Company and RCA Manufacturing Company in a vibration pick-up constructed of Rochelle-salt crystals properly grown and mounted. These crystals have the property of converting mechanical vibration or motion into electrical currents. Thus it is merely necessary to let the vibration to be investigated impart itself to the Rochelle-salt crystal so that voltage variations are set up which may be taken out of the device and looked at on a cathode-ray oscilloscope or measured on a meter.

The device delivers 0.25 volt per 0.001-in. movement at 250 cycles. Up to 1 volt output, the output is directly proportional to the amplitude of vibration. The sensitivity of the crystal increases on a square law as a function of frequency, up to about 3,000 cycles which is the natural frequency of the crystal.

The amplitude of vibration may be calculated from

$$A = \frac{E}{e},$$

where A = amplitude of vibration.

E = r.m.s. voltage generated by pick-up.

e = relative output at vibrating frequency as read from Fig. 81.

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Mead, M. S., Jr. and T. M. Berry describe a portable frequency analyzer for determining the noise spectrum of machines, etc., in the *Gen. Elec. Rev.*, August, 1934, p. 378. This paper gives curves showing the noise output of an electric refrigerator as an example.

Veinott, C. G., Measurement of Noise from Small Motors, *Elec. Eng.*, December, 1934, p. 1625.

Noise Measurement, *Electronics*, April, 1935.

Haynes, F. B., Integrating Noise Meter, *Rev. Sci. Instruments*, October, 1935. Uses a watt-hour meter in the plate circuit of an amplifier tube.

Electron-tube Electrostatic Voltmeter.—The use of an amplifier tube in an inverted circuit, *i.e.*, the grid and plate are

reversed, has been suggested as a voltage step-down device[1] and as an electrostatic voltmeter.[2] In the first application, the tube acts as a voltage reducer instead of an amplifier. The plate-cathode path is the input; the grid cathode becomes the output.

In the second application, that of a low-range electrostatic voltmeter the same connection is used, as shown in Fig. 82. The tube has an infinite input resistance, and with three flash-light cells acting as the sole source of potential, voltages of the order of 20 volts may be read easily with a 200-μa meter.

Voltage Applied at **E**
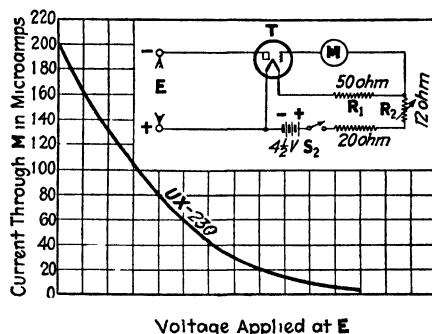
Fɪɢ. 82.—Circuit and response of electron-tube electrometer.

Cosmic-ray Impulse Counter.—Various electron-tube methods of recording the passage of cosmic rays have been devised. That described by Johnson and Street[3] possesses interesting features from the standpoint of electron-tube amplifiers. Each of three Geiger-Müller counters is connected to the grid of a tetrode, the negative pulse produced by the cosmic-ray passage cutting off the plate current of the tube. Since the plate current is reduced to zero, the voltage across the load of this tube rises. In the second tube, this positive pulse produces a high plate current which reduces the voltage across its load and in effect produces a negative pulse which is applied to the grid of the third tube.

The first two tubes are high-gain tubes; the third is a low-mu stage. Several such stages are connected together, the plates of the final tubes, low-mu triodes, are connected in parallel through a

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[1] Tᴇʀᴍᴀɴ, F. E., *Proc. Inst. Radio Eng* , April, 1928.

[2] Kᴏᴇᴄʜᴇʟ, W. P., *Electronics*, September, 1933.

[3] *J. Franklin Inst* , March, 1933. A portable double Geiger counter described in *Rev. Sci. Instruments*, July, 1933, by R. D. Bᴇɴɴᴇᴛᴛ, J. C. Sᴛᴇᴀʀɴᴇs, and W. P. Oᴠᴇʀʙᴇᴄᴋ, uses 32-type tubes.

0.2-megohm resistor. The voltage appearing across this combined output circuit is passed to the grid of another triode which is so biased that it does not respond unless an impulse arrives simultaneously from all the parallel counters. After another stage of inversion (changing the negative pulse to a positive) so that the resultant will operate a counter, the passage of the cosmic ray is finally recorded by a Western Electric relay which operates the escapement arm of an Ingersoll watch. The passage of 60 impulses per second may be recorded.

The values of resistance and capacity are chosen to give the proper time constants to reduce the time of the impulse or to prevent registering accidental coincidences.

Cosmic-ray Hodoscope.[1]—This is an instrument for observing and studying the detailed phenomena of the cosmic radiation by making visible the paths of the penetrating corpuscular rays through a continuous region of space. It consists of a large number of small Geiger-Müller cylindrical condensers stacked in a two-dimensional array or bank. Each of the individual counters in the bank is connected through one stage of amplification to a neon glow lamp which occupies a position on a panel corresponding to the position of the counter in the bank. The discharge of the counter, initiated by an ionizing ray, thus produces a flash in the lamp to which it is connected. The hodoscope therefore accomplishes to a limited extent the same purpose as the Wilson cloud chamber and it has the advantage of being continuously sensitive.

Under normal operation with the grid at the cathode potential, the voltage applied to the plate and therefore across the lamp is small compared with that across r and is less than the flashing potential. If, however, the counter C is discharged by an ionizing ray, the negative pulse delivered to the grid raises the plate impedance to a value which is large compared with r and the potential across the lamp rises to the flashing voltage. The current through the lamp is then limited by the resistance r.

[1] *J. Franklin Inst.*, September, 1933. See also DUNNING, JOHN R., Amplifier Systems for the Measurement of Ionization by Single Particles *Rev. Sci. Instruments*, November, 1934, p. 387; RAMSEY, W. E., and M. R. LIPMAN, Circuit for Analysis of Geiger Counter, *Rev. Sci. Instruments*, April, 1935; GALLEY, D. P., Geiger-Müller Counter for Measurement of Diffracted Mo K X-rays, *Rev. Sci. Instruments*, September, 1935.

When the grid potential again drops to that of the cathode, the potential across the lamp falls below the extinction point and the lamp is again dark.

An Electron-tube Recording Potentiometer.[1]—A high-speed recording instrument suitable for making permanent records of variations in small d.c. volt-ages, such as developed in thermocouples, and employing amplifier tubes and grid-controlled gaseous rectifiers, has been produced by engineers of the Leeds and Northrup Company. The instrument is a high-speed null recording device

Fig. 83.—Circuit of cosmic-ray counter.

in which the usual mechanical system composed of a galvanometer and balancing system has been replaced by a faster electrical system.

The circuit for the ingenious device is shown. The output of the thermocouple, or other source, is, of course, direct current and can be amplified only with difficulty. If, however, it is
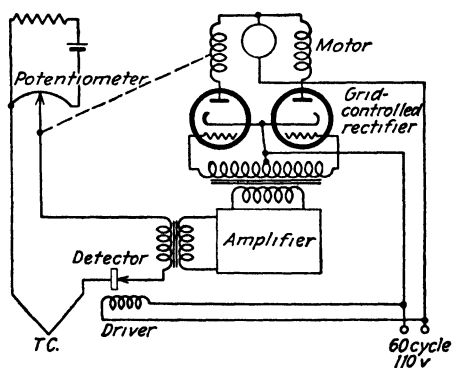
Fig. 84.—Recording potentiometer using vacuum and gaseous triodes.

modulated, amplification is not difficult at all. Therefore, in series with the thermocouple is a microphone mechanically driven by a 60-cycle armature. This modulated current is applied to the grids of push-pull controlled rectifiers. The plates of these

[1] See *Instruments*, November, 1933, p. 211, for a description of this instrument known as the Speedomax.

tubes are supplied from the same a.c. source as the modulating armature and therefore have the same phase.

The unbalance current (thermocouple) may flow in either direction, and the phase of the grid voltage to the rectifiers depends upon this direction. Either one or the other of the two rectifiers will conduct current if an unbalance current occurs. The plate currents of the rectifiers drive a split-field series-reversing motor which drives the potentiometer slide wire which balances the system.
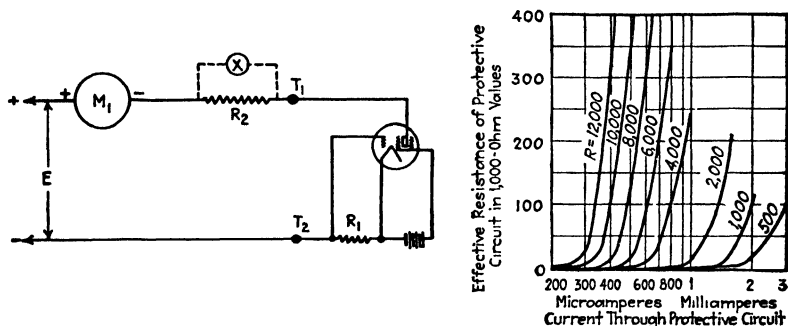
Fig. 85.—Circuit and response of device for protecting sensitive meters.

By coupling a tachometer magneto to the shaft of the driving motor and using its e.m.f. to oppose the e.m.f. generated by the thermocouple circuit, tendency to overshoot is eliminated. Since the e.m.f. generated by the magneto varies as the rapidity of the change, sudden unbalances are ironed out in their effect.

The recorder pen can cover the 10-in. chart width in 2 sec. without difficulty from overshooting.

Protecting Meters by Electron Tubes.—The possibility of damaging sensitive d.c. microammeters and galvanometers due to accidental application of high voltage always causes the engineer and laboratory worker considerable apprehension. The ideal protection for a low-range microammeter is a resistance which at any current within the range of the meter being protected has zero resistance. At any higher current value the resistance becomes infinite.

A method of utilizing a vacuum tube, a resistor and a source of low voltage has been described.[1] The circuit is given in Fig. 85, where the applied voltage is E, the meter being protected

[1] KOECHEL, W. P., *Electronics*, May, 1933.

is M_1, the protective circuit inserted into the system under measurement by using terminals T_1 and T_2. In other words, this protective circuit is connected as a series circuit. By proper choice of the resistor R_1, and screen-grid voltage values, this circuit will have a sharp cut-off at any current value desired, for example, 12,000 ohms for a 300-microampere meter. If, however, an accidental short circuit occurs at X, the most current that will flow will be 460 μa assuming a voltage of 250 at E.
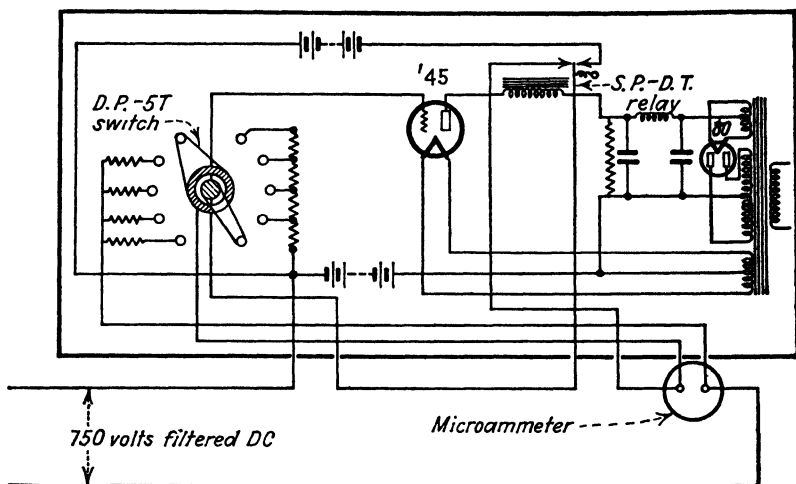
FIG. 85*A*.—Electronic circuit breaker.

Another method of protecting a meter is due to H. C. Frost.[1] In testing automobile spark plugs for insulation and leakage characteristics, a d.c. voltage of 750 volts is put across the plug in series with a microammeter. In case the spark plug is short-circuited the meter will be damaged or ruined. The circuit shows a tube operating a circuit breaker when the current through the microammeter becomes high enough to damage it. The switch controls the value of resistance in series with the supply-voltage line and therefore controls the value of current at which the circuit breaker operates. The voltage drop across this resistor is applied to the grid of the 45.

Flue-gas Control.—A method of recording sulphur acids in flue gases has been devised by Fox and Groves.[2] The gases

[1] *Electronics*, May, 1936.
[2] *Chem. Ind.*, January, 1932.

are absorbed by dilute hydrogen peroxide and the concentration measured by means of a glass electrode. The voltages of this electrode are amplified by a two-stage direct-coupled amplifier and operate a thread recorder.

Telemetering System (Esterline-Angus).—A remote metering system using a vacuum-tube detector is illustrated in Fig. 86A. In this case the tubes are supplied with alternating current on the anode and a variable d.c. voltage on the grid. The tubes rectify the alternating current and the rectified current, which passes out through the line, depends upon the value of the grid voltage (bias) at the instant.
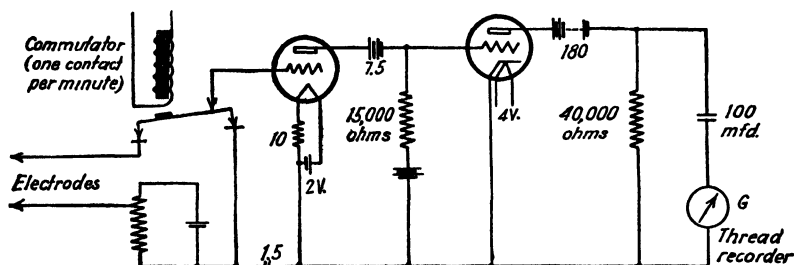
Fig. 86.—Circuit of flue-gas recorder.

The system consists of a meter to measure the quantity to be transmitted, the tubes which convert variations in meter reading into direct current by rectification, and a recording instrument at the receiving end.

In the diagram M_1 represents a primary meter, or a member actuated by it. Above it is M_2, which is the movement of a D'Arsonval meter. The latter carries a contact which floats between two contacts carried by the moving member of the primary meter. Two of the tubes are detectors mentioned above. The third is a two-element rectifier to furnish the bias voltage for the grids of the detector tubes.

If the reading of the primary meter increases, contacts at A are closed, which causes the grid bias to decrease, thereby increasing the plate current. This increased current will flow through the D'Arsonval movement and will continue to do so until this movement has taken up a position such that the contact before mentioned is broken.

The cycle is reversed, of course, if the primary meter decreases in reading. The meter element at the receiving end of the line

will take up a position according to the change in current flowing through the line and will follow the movement of the D'Arsonval meter.

By this method it is possible to transmit the position of moving members of instruments having very low torque. Quantities
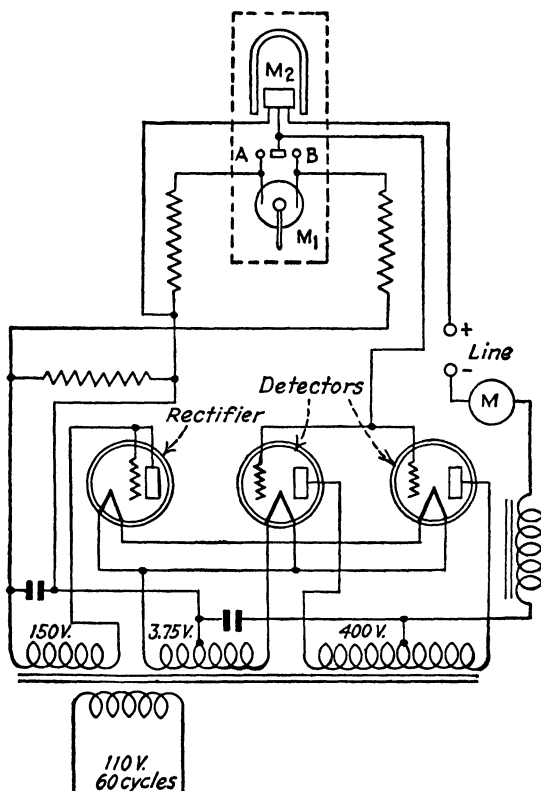
Fig. 86A.—Circuit of Esterline-Angus telemetering system.

that can be transmitted are a.c. and d.c. voltage, current, kilowatts, power factor, speed, water level, etc. The power consumption is approximately 150 watts; the maximum value of transmission current is 50 ma. Over standard transmission lines, indications can be transmitted up to 50 miles.

Tube Control of Motors.—Ryder[1] has described several circuits which enable the use of ordinary radio-receiving tubes

[1] RYDER, J. D., *Electronics*, April, 1936.

for the control of small a.c. motors.   Figure 87 illustrates the control of a self-starting reversing synchronous motor of the electric-clock type.   Two independent field windings are provided with the position of the copper shading rings reversed to
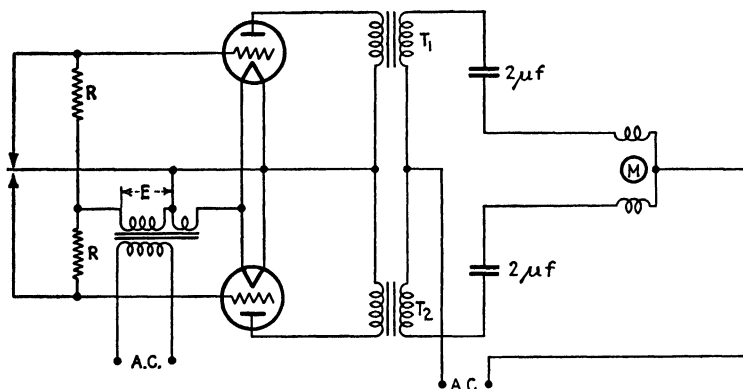
Fig. 87.—Circuit for controlling a motor by electron tubes.

obtain rotation in either direction.   When contact is made in the grid circuit, one of the tubes is energized so that plate current will flow.   This reduces the impedance of the winding in series with the motor field winding and the line and permits the motor
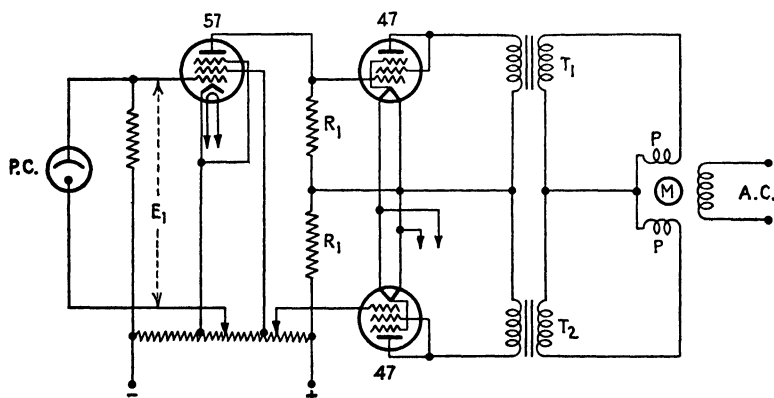
Fig. 88.—Motor-control circuit of greater possibilities than that of Fig. 87.

to run.   Normally the tubes are biased to the point where no current flows.

Another circuit of somewhat similar design but greater capabilities is shown in Fig. 88.   This uses a small reversing induction

motor with wound shading poles such as are commonly used for driving valves, dampers, or recording devices.

The motor is capable of much greater power output than that used for the previous circuit, the input to the field running as high as 25 watts, and the motor efficiency being quite reasonable. Besides the advantage of greater power output, the motor speed may be varied over a range of 4 to 1 in either direction, or a differential action may be obtained, the motor speed and direction varying according to the difference in the excitation of the shading poles.
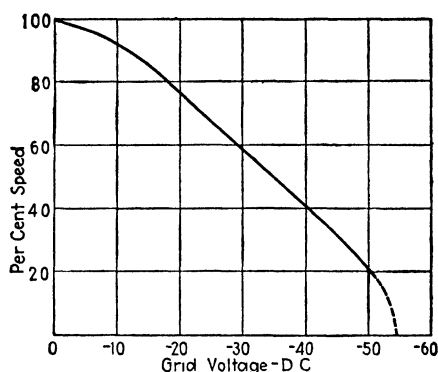
FIG. 89.—Motor-control characteristic.

Each of the motor shading pole windings is connected to the primary of a transformer T_1 or T_2, the secondary of which is connected to the plate-filament circuit of a vacuum tube as in the previous circuit. The tube grid circuits may be arranged in a number of ways, one of which is shown in Fig. 88. The only requirement of the grid input is that sufficient voltage be supplied to swing the grids from cutoff up to approximately zero voltage.

The field of the motor is continuously excited from the a.c. line, and the wound shading poles, acting as small transformer secondaries, have induced in them about 25 volts.

Another motor-control system, used for controlling the drive of an astronomical telescope is shown in Fig. 90.

The frequency desired is generated in the resistance-stabilized oscillator, at the left in the diagram. The thermionic frequency control in the second, or middle, section comprises a pair of tubes whose grids are excited by the frequency generated at the left.

The plate voltage is supplied by the speed-controlled device and has a frequency proportional to its speed. The instantaneous magnitude of the plate current is a function of the instantaneous plate and grid voltages or, more simply, of their phase difference. This plate current, acting on the speed-controlled device, maintains synchronism between the left-hand and right-hand elements.
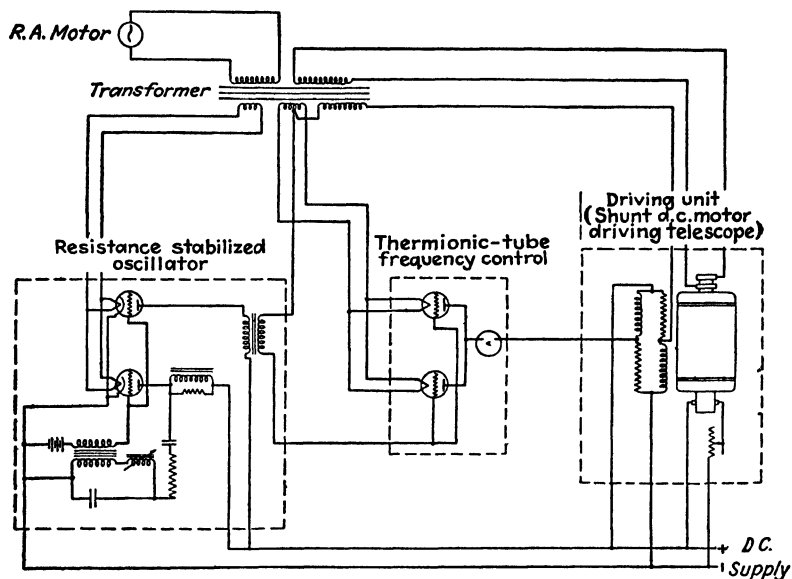
Fig. 90.—Telescope drive controlled by accurate frequency adjustment independent of load changes.

The driving unit is a shunt-wound d.c. motor operating the telescope, with slip rings installed to supply plate voltage for the control tubes and filament current for all tubes. The shunt field is opened at its electrical center, and the circuit is completed by means of fixed resistances, thus forming a bridge circuit. The output of the plates of the control tubes of the center section is connected to this bridged circuit.

At the Lake Angelus, Michigan, observatory of McMath-Halbert, the range of control is from 57 to 60.5 cycles per second. The cost of the electronic outfit has proved less than that of a first-class, weight-driven, pendulum-controlled driving clock of conventional design.

A synchronous motor with electronic connection between field coils forming a mechanical coupled variable-frequency oscillator has been described by P. B. King.[1]   Several circuits are described in the reference as to the type of control, *i.e.*, magnetostriction, controlled rectifiers, tuned circuits, etc.

Automatic Synchronizing.—The use of an amplifier for synchronizing is shown in Fig. 91 taken from Holland.[2]   The network at the left produces two voltages, one of which drops out a relay *C* a definite *angle* in advance of synchronism, and the other

Fig. 91.—Circuit for automatic synchronization.

of which operates a differential relay *D* at a definite *time* equal to the breaker-closing time, in advance of synchronism.

If the relay *C* operates early enough before relay *D*, the significance is that the frequency difference is not excessive, and a main auxiliary relay *F* acts (when *D* operates) to give the breaker-closing indication.   If relay *D* operates ahead of relay *C*, the significance is that the frequency difference is excessive, and an auxiliary relay *E* drops its contacts open so that the breaker-closing indication cannot be given.

A compensated amplifier is interposed between relay *D* (which has two coils, one for each tube) and the voltage that controls it. A component of this voltage is provided by a circuit which compensates for differences between the two source voltages so that the definite time of advance of relay *D* is not seriously affected by unbalanced voltages.

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[1] *Electronics*, January, 1936.

[2] HOLLAND, W. A., *Instruments*, April, 1935.

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CHAPTER IV

GASEOUS TRIODES

Gaseous Triodes.—In the tubes just described it is of vital importance that as few gas ions as possible exist in the envelope enclosing the elements. In such a high-vacuum tube the grid has almost complete control over the anode or plate current. It can increase it or decrease it. But, if only a few gas ions are admitted to the tube, the grid loses its modulating control and the relation between grid voltage and plate current assumes a radically different characteristic. In a gaseous triode the grid has only one function: to permit or prevent the flow of anode current. It cannot modulate it to any less degree than this. The anode current is either all or nothing. To stop flow of current the anode voltage must be removed.

The vacuum triode is essentially an amplifier of power. The variation of voltage on the grid produces a flow of current in the anode circuit. The gaseous triode, on the other hand, is essentially a relay tube acting much as a mechanical contactor with the advantage that there are no moving parts and no contacts to pit or wear out. There is another difference between the vacuum tube and the gas tube. The power that can be handled by the latter is very much greater than the maximum power controlled by the amplifier.

The reason for the greater flow of power in the gaseous triode is the fact that 10,000 times as many electrons may be packed into it as into a high-vacuum tube. The electron density may be 10^{12} or 10^{13} per centimeter cube compared to 10^9 in the highly pumped tube.[1]

[1] HULL, A. W., and IRVING LANGMUIR, Control of An Arc Discharge by Means of A Grid, *Proc. Nat. Acad Sci*, vol. 51, No. 3, pp. 218–225, March, 1929. KNOWLES, D D., and S. P. SASHOFF, Grid-controlled Glow and Arc Discharge Tubes, *Electronics*, July, 1930; *Elec. J.*, August, 1930; HULL, A. W., Gas-filled Thermionic Tubes, *Trans. Am. Inst. Elec. Eng.*, July, 1928, HULL, A. W., Characteristics and Functions of Thyratrons, *Phys.*, February, 1933.

Because of the greater number of electrons in a gaseous tube, amperes may flow through it compared to milliamperes in a high-vacuum tube. Furthermore, these currents will flow through the gaseous tube with a voltage loss of only 10 to 20 volts. On the contrary, to produce a current flow of milli-amperes, a vacuum tube must be supplied with several hundred volts. For example, in a power tube such as a 210 type, a plate current of 50 ma. will flow if the cathode-plate voltage is 350. A grid-controlled rectifier of the same bulb size, however, will carry 0.5 amp. with only a 10- to 20-volt drop in the tube.
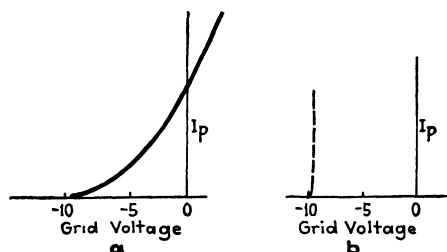
Fig. 1.—Characteristics of vacuum and gas tubes.

The most powerful triode of the high-vacuum type has a plate current of about 6 amp. which requires about 15,000 volts. This tube will deliver about 100 kw. of power. The largest gaseous triode has a rated current of 600 amp. maximum, 100 amp. average, at a plate voltage of 1,500. A mercury-arc type has been built which has 12 anodes, each of which will carry 4,000 amp. at a d.c. voltage of 1,500. Experimental tubes of the general type under discussion have been operated in the laboratory for long periods at 150,000 volts.

The Grid-controlled Rectifier.—Various names have been applied to tubes of this general type, for example, thyratron (General Electric) and grid-glow tube (Westinghouse). The characteristics of such tubes differ radically from those of high-vacuum tubes. In a tube of the latter type with a characteristic like the full lines in Fig. 1a, no current flows if the grid voltage is 10 volts or more negative. If the voltage is made less negative, more current flows according to the smooth curved line.

Thus in a high-vacuum tube the grid bias may be thought of as adding to or subtracting from the space charge so that electrons have more or less difficulty in reaching the plate. There is no

discontinuity in the characteristic of plate current as controlled by the grid voltage.

In a gaseous tube,[1] however, conditions differ widely between the no-current and the current-passing states. Before sufficient ionization takes place for the glow to be established the tube resembles a high-vacuum tube in that the space charge prevents the flow of current. If the grid voltage is made less and less negative, nothing happens until a certain critical voltage is reached. Then ionization takes place, and the full anode current flows, limited only by the emission of the cathode and the external load resistance. There is a sharp discontinuity in the characteristic. If the tube passes 1 amp. when conducting, it will pass 1 amp. no matter what the grid voltage is so long as it is sufficiently positive (or so little negative) that conduction takes place.

In practice the tube is not biased close to the trigger point, since slight changes in applied voltage, transients, slight changes in characteristic with age, or between tubes may cause the tube to fire. In this respect the gas tube is not so reproducible as a high-vacuum tube. The gas tube is usually biased some distance from the critical value of grid voltage, and then, to start the tube conducting, a voltage considerably greater than the critical trigger voltage is applied. The fact that it is desirable to substitute a new tube at the end of life of an older one without circuit changes contributes to the foregoing practice.

Why does the grid lose control after the discharge has begun? Langmuir and Hull explain it by stating that a sheath of positive ions, produced by the ionization process, surrounds the grid and shields it from what is going on in the tube. Hughes[2] points out that the grid does not change much in actual voltage with respect to the cathode, owing to the practice of using a resistance in series with the grid to limit the grid-current flow. No matter what current flows, the voltage drop along this

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[1] The pressure varies depending upon the gas and upon the voltage at which the tube is to be worked, *e g.*, mercury at pressures of from 0.001 mm. to 0.050 mm., the lower pressure for high voltage and rapid de-ionization; argon and helium are used at pressures of about 3 and 10 times the above figures. At low voltages, pressures double those above may be used, for example, argon at 0.050 mm.

[2] HUGHES, EDWARD, *Electrician*, Mar. 6, 1936.

resistance is such as to maintain the grid at a slight positive potential.

Thus the grid in a gas tube is a one-way sort of control. It can prevent the flow of current; but once the tube has fired, the grid cannot stop the flow of electrons. By making the grid wires very close together, a greater measure of control is secured;
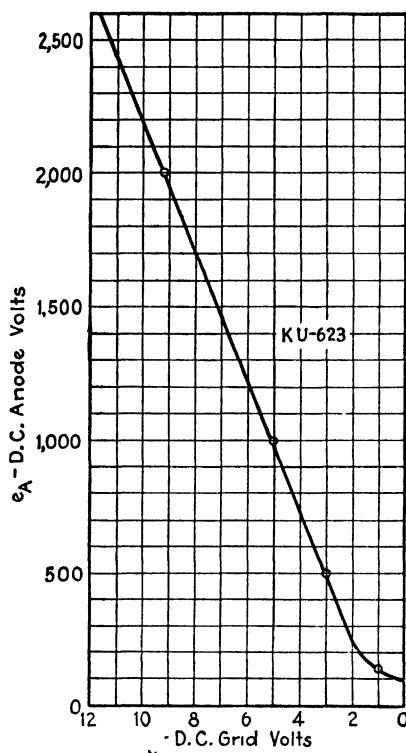
Fig. 2.—Typical gas triode characteristics.

but in practical tubes the grid might as well not be inside the envelope once the tube is passing current.

Gas Triode Characteristics.—The characteristics of a typical gaseous triode are shown in Fig. 2. While this curve resembles that of a vacuum triode, it is really very different. In the first place the coordinates are plate voltage and grid voltage, while a vacuum-tube characteristic would be defined in terms of plate current and plate or grid voltage. The curve in Fig. 2 gives the values in plate voltage and grid voltage at which current will

start to flow. Thus if the anode voltage is 2,000, plate current will flow if grid voltage is made less negative than -9, for example, 8 volts. If the plate voltage is raised to 2,500 volts, a more negative grid voltage (-11) is required to prevent the tube from passing current. (In technical jargon the tube is said to "fire" when it passes current.)

Thus for each value of plate voltage there is some value of grid voltage which will prevent firing; if the grid is more negative, nothing happens—but any value less negative than this permits the tube to fire. In such tubes there is only one way to stop the flow of current once it has started, *i.e.*, by removing the plate voltage. Then after a time long enough for the ions to recombine with negative electrons and again to become neutral atoms of gas or vapor, the grid regains control and the plate voltage can be reapplied without current flowing.

Cathode Structure.[1]—In gaseous tubes cathodes of greater efficiency can be used than are possible with high-vacuum tubes. This efficiency, the ratio between the electron emission and the power required to keep the cathode hot, cannot be continuously increased without affecting filament life. Efficiency increases with temperature; but life usually decreases with temperature, since at the higher temperatures the filament evaporates at a higher rate.

In cathodes used for high-vacuum tubes little can be done to increase the efficiency except to use the proper choice of emitting surfaces or substances. If holes are made in the cathode to conserve heat, the electrons do not get out because of the space charge. Emission, therefore, does not increase. In gaseous tubes, however, the situation is entirely different so that highly efficient cathodes are possible. Here the electrons leaving from deep cavities in the cathode can escape because the space charge is neutralized by the positive ions. Such electrons will freely emerge from cavities $\frac{1}{8}$ to $\frac{1}{4}$ in. wide and 4 in. deep. Such electrons will flow around corners—heat radiation, on the other hand, must proceed in straight lines. The electrons escape easily but heat escapes from these cavities much less easily. Two highly efficient types of cathodes are shown in Figs. 3 and 4. The heat-radiating surface is essentially that of the envelope

[1] See Lowry, E. F., Cathodes for Grid-controlled Rectifiers, *Electronics,* December, 1933.

of the cathodes, though the electron-emitting surface is many many times larger. They may be made still more efficient by surrounding them with heat-reflecting shields. There is one compromise, however, in such increased efficiency. This is the fact that the more efficient a cathode is made, the longer will be the time required to reach equilibrium after heater voltage is applied. In some cases, this becomes an important factor, and it is necessary to compromise between short heating time and high emission efficiency.

Thus the cathodes for gaseous tubes may be constructed so that the emitting surface is heat insulated on the outside, and the only appreciable loss of heat will occur at the open end or from the holes through which the electrons emerge. In a typical structure vanes coated with the emitting material are protected from heat loss by concentric cylinders. The total emitting area is 250 sq. cm., and at a heat loss of 60 watts the normal emission is 75 amp. In another case the emission comes from a series of nickel disks coated with barium.
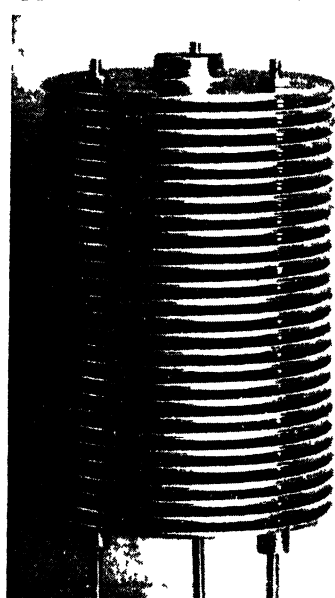
Fig. 3.—Efficient cathode, heated by a centered tungsten wire, used in mercury-vapor tubes.

This structure is surrounded by the heat-protecting cylinder which is perforated. In this tube an emission of 600 amp. is obtained at an expenditure of only 300 watts for heating the filament. An open or unshielded cathode of the same area would have an emission of only 15 amp.

The power cost for supplying electrons in such heat-insulated cathodes is small; for large cathodes it is approximately 0.5 watt per ampere of emission. Since, in many practical circuits, the anode current flows for only a small part of the time, usually from one-half to one-twelfth of the time, the average power required to heat the filament is from 1 to 6 watts per ampere of average current.
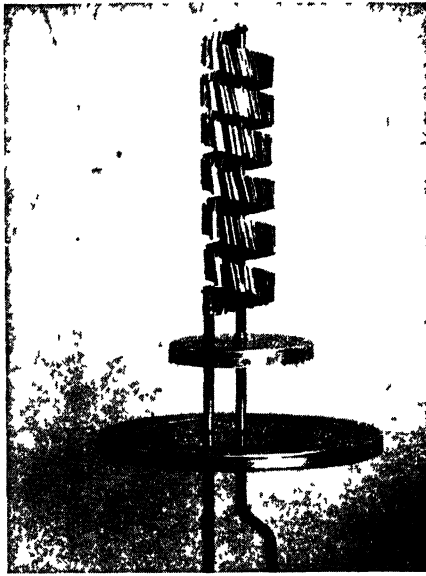
Fig. 4.—Coated filament crimped to give mechanical stiffening and to shorten length. This cathode is of the type used in high-power rectifiers.
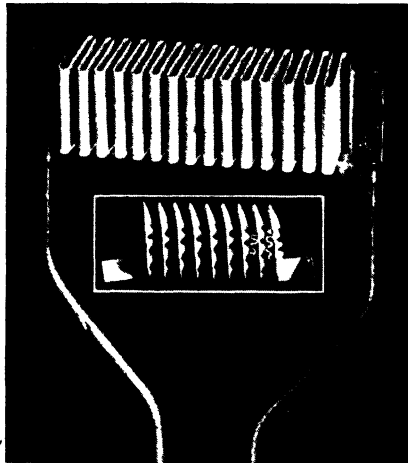
Fig. 4A.—Gas-tube cathodes. The upper has 22.5 sq. in. emitting surface, heats in 2 min., requires 200 watts, and has a capacity of 65 peak amperes. The inset shows 5-volt 20-amp. cathode, 1 in. long, with an effective length of 14.5 in. It delivers 22.5 peak amperes.

The power lost in the anode circuit of such tubes is small. The sum of the cathode and voltage drop losses for a mercury-vapor tube with thermionic cathode is about 7 watts per ampere under most favorable conditions. With caesium vapor these losses decrease to 3 watts per ampere. Despite unsolved problems in connection with caesium tubes, they promise a great deal. A mercury-arc rectifier or grid-controlled rectifier with mercury-pool cathode loses about 20 watts per ampere, with the possibility of a reduction to as little as 12 watts per ampere with caesium.

Proper choice of tube and circuit will provide efficiencies of 95 to 99 per cent.

Comparison of Vapor- and Gas-filled Tubes.—Several gases have been used in grid-controlled rectifiers. For tubes to be operated on low voltages, neon or other insert gas is used, while for higher voltages mercury vapor is generally employed. The neon or gas-filled tubes have the advantage that they are unaffected by temperature, while the mercury-vapor tubes are critical to temperature changes. Neon tubes have considerably higher voltage drop than mercury tubes. Argon-filled tubes, however, have a difference in drop of only 1 or 2 volts from mercury-vapor tubes. The FG-81 is a good example of an argon tube. Because of the tendency to flash-back, or conduct current during the part of the cycle when the anode is negative, neon or other gas-filled tubes are restricted to lower voltages.

Ionization and De-ionization Time.[1]—A definite time is required for ionization to occur before the full anode current builds up. This time is very small, of the order of a few microseconds. It must not be understood that the times of ionization or de-ionization are constants of a tube like mutual conductance. These times vary with temperature, gas pressure, anode voltage, etc.

The time required for de-ionization to take place is much longer because when the anode or ionization voltage is removed from the tube, the anode current will fall to zero, but the ions and electrons will not immediately disappear. Until de-ionization occurs and the ions and electrons have diffused to the walls of the tube or recombined in the space, the grid cannot regain control. Therefore, after the anode potential is removed, a

[1] See BERKEY, W. E., and C. E. HALLER, Reignition Potential of Hot-cathode Grid Glow Tubes, *Elec. J.*, December, 1934, p. 483.

certain time must elapse before the anode is made positive if the grid is to regain its power to control the starting of the discharge. In normal tubes this time varies from about 10 to 1,000 microseconds. In typical tubes this time varies directly as the gas pressure, inversely to the $\frac{3}{2}$ power of the grid voltage, and is directly proportional to the 0.7 power of the anode current. On 60-cycle circuits this de-ionization time is not of great importance, but at higher frequencies the time required to regain control of the plate current becomes a limiting factor. In fact the grid-controlled rectifier cannot be operated at frequencies higher than 5,000 cycles. On inductive load circuits, de-ionization times as short as 50 microseconds are sometimes limiting factors.

Typical Tube Characteristics.—In general there are two types of tube— positive and negative controlled. In the one case the grid voltage for the flow of current is positive with respect to the cathode. In the other case the tube fires for some negative voltage on the grid. More tubes in actual use employ the negative characteristic.

FIG 5 —Argon-filled triode control characteristic.

The important characteristic for a grid-controlled rectifier is a curve showing the proper combination of grid and plate voltages which will just permit current to flow. For example, if a d.c. voltage is put across the cathode-anode circuit of such a rectifier, the plate will always be positive with respect to the cathode. Then if the variable arm of a potentiometer, as in Fig. 6, is connected to the grid, a certain position will be found corresponding to some positive (or negative, depending upon the tube type) value of grid voltage (with respect to the filament) at which current will flow. After this takes place, no amount of adjustment of the slider will change the flow of current. The grid has lost control. The only way to regain this control or to stop the passage of current is to remove the plate voltage.

If the plate voltage is reduced, a higher value of positive grid voltage (or less negative) is required to start the current; if the

plate voltage is increased, a more negative grid voltage will initiate the discharge.   A line connecting these combinations of grid and anode voltages will constitute the characteristic of the tube under the conditions of d.c. control.

Such a curve is shown in Fig. 6.   For this particular tube, KU-636, with a positive potential of 200 on the plate, the slider must be at the point which will make the grid negative by not more than 2.5 volts before current will flow.   Other combinations of voltages may be obtained from this curve.

Figure 7 shows the characteristics of a tube of the filament type of cathode useful in control circuits where it is desired to actuate the tube with negative values of control-grid voltage.   It is suitable for relay work where current flow is desired in the absence of grid excitation, for example where the amount of grid power is limited.   It has a long de-ionization time (1,000

Fig. 6.—Characteristics of helium tube and d.c. circuit.
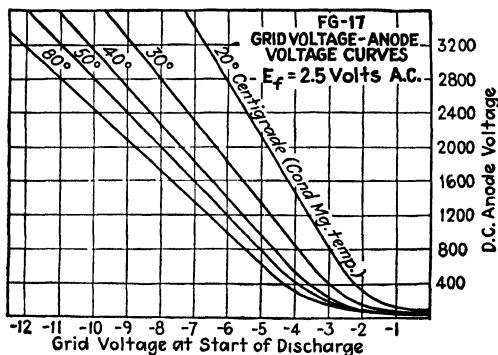
Fig. 7.—Typical characteristics of mercury-vapor triode.

microseconds, approximately) and therefore is not used ın inverter circuits.   It has a quick-heating filament.

Tube Types.—Owing to the fact that there are negative-control and positive-control tubes, as well as three-element and four-element tubes, the number of combinations of characteristics possible at any given current or voltage rating may be very large. It is possible to require as many as 16 different tubes of a given size to satisfy perfectly all the requirements that might be met for gas-filled tubes. In most cases, tubes are not available meeting all of these requirements, since the cost of special types of tubes is, of course, extremely high unless a very large demand for a certain particular type makes it economic to build a tube for this particular application.
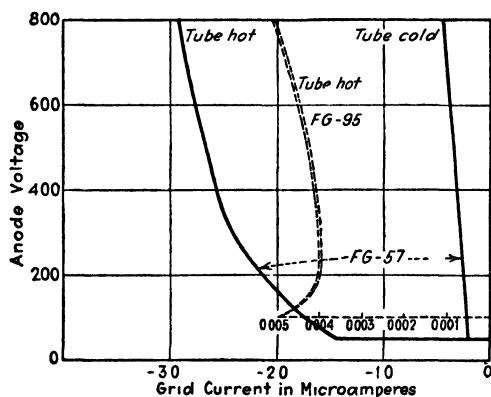
Fig. 8.—Grid currents in three- and four-element tubes, hot and cold, at start of discharge.

Shield-grid Tubes.[1]—Since the bias voltage on a tube of the sort under discussion is always somewhat greater than that required to prevent the arc from starting, and since to make certain the arc formation a grid voltage greater than the critical value is applied, a certain grid power is necessary. This power must be supplied by the driving force. The grid current after discharge is many times the value before discharge. This is not generally detrimental, since the tube has already been controlled before the grid current after discharge occurs. Under certain conditions it may, however, upset a weak grid circuit, causing incorrect firing of associated tubes, or may result in a condition such as saturation of the grid transformer which may persist after the tube has ceased firing and the grid is again

[1] LIVINGSTON and MOSER, *Electronics*, April, 1934.

trying to exercise its control function, thus distorting the grid input voltage.   The grid current before discharge, however, is a real limitation upon the tube when used with very high impedance grid circuits such as are frequently encountered in photoelectric or other control arrangements.   This grid current invariably produces an impedance drop in these circuits which tends to reduce the actual grid voltage.   In very high impedance circuits this drop tends to make the operation of the tube independent of the intended actuating voltage.   In addition to this,
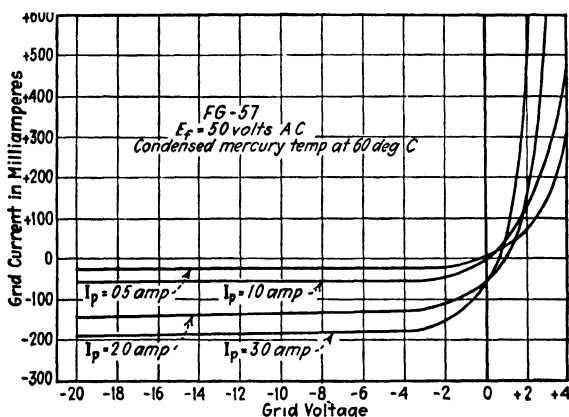
Fig. 9.—Grid voltage-grid current curves for various anode currents (three-element tube).

the impedance drop may vary; for example, as the grid emission changes, owing to the tube warming up under load, the grid current would vary, and thus operation would be made unreliable.

   To overcome some of these difficulties, four element or shield tubes are now commercially available.   Under the same conditions the shield-grid tube will pass much less grid current than the three-element tube.   The shield grid protects the control grid from cathode material sputtered or evaporated from the cathode.   The discharge is protected from extraneous charges which may accumulate on the walls of the tube.   It closes all possible paths between anode and cathode except the opening in the grid baffles adjacent to which the control grid is situated.   The small size of the control grid results in small ion grid current both before and after the discharge.   Thus the power required

by the grid circuit to control the starting of the discharge is reduced, an item of importance in many applications.

There is another advantage of the four-element grid-controlled rectifier. The starting characteristic can be varied by varying the potential at which the shield grid is held, making it possible to have a tube whose starting characteristic can be made either positive or negative, or by impressing a fluctuating potential
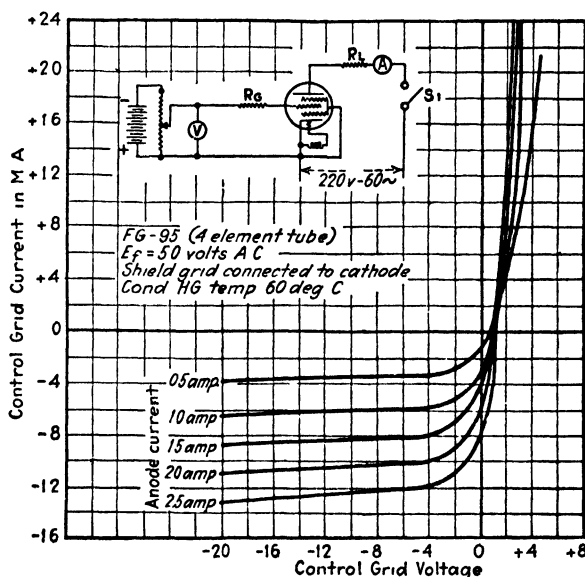
FIG. 10.—Control-grid current after start of discharge in four-element tube.

on the shield grid, the tube can be made to have a negative control characteristic over some portion of the cycle and a positive control characteristic over the remainder of the cycle. By varying the phase relation between the two grid voltages interesting and valuable control effects will no doubt be worked out.

Furthermore, the shield-grid construction tends to prevent transient conditions in the plate circuit from affecting the grid circuit and thus the operation of the circuit. The grid is protected from heat from anode, cathode, or arc stream and therefore there is much less tendency toward secondary emission.

The sole disadvantages of the more complicated tube seem to be its greater complexity (one more terminal) and its slightly higher cost.

Mercury-pool Cathode Controlled Rectifier.—There are many applications where it is desirable to use a tube capable of with-standing severe overloads of short duration.   An oxide cathode tube cannot carry a load beyond the capacity of its filament. To fill such an application, then, such a tube will require a very
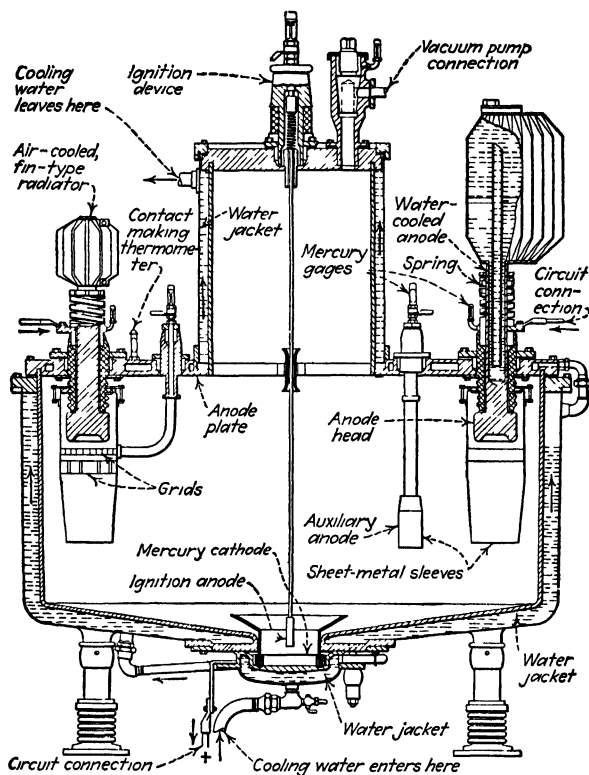
Fig. 11.—Details of mercury-pool grid-controlled rectifier.

large filament which must be maintained at operating tempera-ture at all times.

Mercury-pool cathode grid-controlled rectifiers have been developed to meet the requirement of large instantaneous current demand and still have a very low cost of operation. The cathode is a pool of mercury such as is used in mercury-arc rectifiers.

The primary electrons in this case are obtained by maintaining an arc between a keep-alive electrode and the mercury pool.

When an arc strikes between anode and cathode, a spot is formed on the surface of the mercury pool which serves the same purpose as the filament of the oxide cathode tube, *i.e.*, as a source of electrons necessary to maintain the discharge. This spot, known as "cathode spot," unlike the oxide filament has an unlimited electron-emitting capacity and can, therefore, handle the severest of overloads. The formation of the cathode spot is accomplished by a drop of potential at the cathode. The voltage drop in this case, however, is small, so that the total drop in the tube is between 9 and 11 volts. The breakdown point of this tube is affected by the mercury-vapor pressure which depends on the intervals between operations.

Grid Control of Mercury-arc Rectifiers.—A 12-anode rectifier[1] of this general type rated at 5,000 amp., nominal 625 volts direct current, has been in operation at the Commonwealth Edison Company, Chicago. In it the grid-control equipment is arranged so that the d.c. voltage can be maintained within the desired limit of all loads without the use of tap-changing equipment and without interrupting the flow of power. Grids next to the anodes are made of graphite, are insulated from the anode housings, and the grid leads are brought to the outside of the tank through bushings in the anode plates. The rectifier d.c. voltage is controlled by impressing a suitable potential on the grids by means of these leads to control the instants in each cycle when the anodes are permitted to fire.

The auxiliary apparatus necessary in connection with this control consists merely of a small auxiliary transformer, resistances and the necessary switches and fuses, and, since only a fraction of an ampere is needed to energize the grids, these devices are of very small capacity.

No trouble has been experienced in the operation of this rectifier in regard to blocking action by the grid or with back-fire disturbance, although the voltage is being controlled at currents as high as 6,000 amp. The principal difficulty which had to be overcome was due to delayed picking up of the anodes from no load and a change in the cooling system improved this condition.

[1] MARTI, OTHMAR K., *Elec. World*, October, 1933. See also DURAND, S. R., Metal-clad Grid-controlled Mercury Rectifiers for Radio Stations, *Electronics*, January, 1934.

Extensive investigations carried out in the laboratories of Brown, Boveri & Company, Ltd., in Baden, Switzerland, led to the invention of a new type of grid, making possible the interruption of anode currents of considerable magnitude in vapor or gaseous types of electric power valves without producing an excessive voltage drop in the arc. It is, therefore, possible with this new type of control to interrupt the flow of current at any instant during the firing period. Previous practice had included only the control of the initiation of firing by the grids, the anode current continuing to flow until it had declined to zero at the end of the half-cycle. This new development enables the succeeding anode to pick up current even when its voltage is lower than the voltage of the anode whose current is interrupted. Consequently, the firing periods of the anodes can be advanced by any desired angle, thus resulting in a leading power factor. Some of the new possibilities from this development of the grid-controlled power valve are immediately apparent, namely, as a static condenser, for compensating lagging current, for frequency changing and, as a matter of fact, for the universal control and conversion of power. This development is therefore a marked advance in the electronics art. Grid control of mercury valves opens up wide possibilities for the use of this valve in motor applications, power-factor correction, inversion, switching, etc.

The time of potential change on the grid from negative to positive determines the time at which current flow is initiated from the anode. Therefore, by arranging the grid control to change from negative to positive at a given instant in each succeeding half cycle, when the anode is positive with respect to the cathode, any proportionate part of the positive half cycle may be allowed to flow through the rectifier. Thus greater or less amounts of the current available from the a.c. supply may be allowed to pass through the rectifier with corresponding changes in the average d.c. output voltage.

In a proposed new design the grid, according to the polarity of the potential impressed upon it, can not only initiate current flow at any time during the cycle but can also stop it at any time. This development, in effect, gives to the mercury valve characteristics comparable to those of the vacuum tube, and opens

up to the mercury device, with its capacity for operation at low arc drop voltage and high current values, many of the possibilities of application promised by the vacuum tube.[1]

The Ignitron.—A new type of controlled rectifier has been developed as the result of a discovery by Slepian and Ludwig of a new method of initiating the discharge. By immersing certain materials, a carborundum crystal, for example, in a mercury pool and then passing current from the crystal to the mercury the start of the arc is forced. At a definite value of voltage and current a small spark occurs at the junction and immediately grows into the cathode spot of an arc. If an anode is properly placed and held at a positive potential with respect to the arc, the latter will be transferred to the anode and thereby initiate the discharge. This process may require only 25 micro-seconds. Thus the discovery makes possible a mercury-pool controlled rectifier with the advantage of practically unlimited emission, and therefore a high overload capacity. Furthermore, it requires no delay when put into service. The life of the cathode, and therefore the tube, is longer than the hot cathode, or thermionic type. Compared to the conventional mercury-pool tube, the ignitron is simpler, and has much less tendency to arc back.

Fig. 12.—G. E. glass-envelope water-cooled ignitron tube type ZG–238.

Each pool of a conventional pool-type rectifier requires a starter of some kind to form the arc and a keep-alive transformer and reactor to maintain the arc. At least 5 amp. are required in the keep-alive circuit to insure stability. In addition to the wasteful consumption of energy, this keep-alive circuit tends to produce ionization in single-anode tubes, and therefore on the inverse cycle tends to increase troubles from arc-back. The

[1] For an excellent description of electrically energized grids for controlling mercury-arc rectifiers and inverters, see Allis-Chalmers Manufacturing Co., *Bull.* 1176, March, 1936.

anodes are placed in anode arms to prevent arc-back thereby complicating the structure and increasing the size, especially since each pool requires keep-alive equipment.

The ignitron has no keep-alive and no anode arms. Three such tubes (one for each phase) will replace a conventional rectifier with less auxiliary equipment, lower replacement cost, and better performance.

The ignitron, then,[1] consists of an evacuated vessel containing a mercury pool having dipping into it a small rod of resistive material, and having opposite it, and in as close proximity as possible, the other main electrode or anode. Electrical connections to pool, igniter, and anode are brought out through the vessel.

Silicon carbide and boron carbide are the two materials most generally used for igniters, although other materials may be used. The igniter current for starting the cathode spot is usually less than 20 amp., and the igniter voltage for this current about 50 volts.

In use, a properly timed current pulse is given to the igniter at the beginning of each desired current-carrying period. At the end of each period the cathode spot automatically goes out and is not reestablished until the current pulse is given again to the igniter at the beginning of the next following current-carrying period. Thus in each current-obstructing period there is no cathode spot on the mercury to induce arc-backs on the adjacent anode.

Ignitrons are now used quite extensively for controlling the currents used in spot welding stainless steel, aluminum, and other metals. In this application, pulses of current of large magnitude but carefully controlled short duration must be fed into the weld. Two ignitrons placed in the primary circuit of a welding transformer as in Fig. 13 permit the large currents to be controlled by merely controlling the grid potentials of the auxiliary thermionic cathode tubes. Glass ignitrons can pass single-cycle pulses of 1,000 amp. for making spot welds at 60 spots per minute. For larger powers, water-cooled metal ignitrons are used. These can pass single-cycle pulses of 3,500 amp. sixty times per minute.

The most convenient method of obtaining the proper current

[1] Slepian, Joseph, Electrochemical Society, Cincinnati, Ohio, Apr. 23–26, 1936.

pulses to the igniter is usually to connect the igniter terminal to the anode externally through a small thermionic cathode tube. For example, in a simple rectifier circuit, as in Fig. 14, the igniter thermionic cathode tubes may be simply rectifying tubes. When a main anode becomes positive, current flows through the
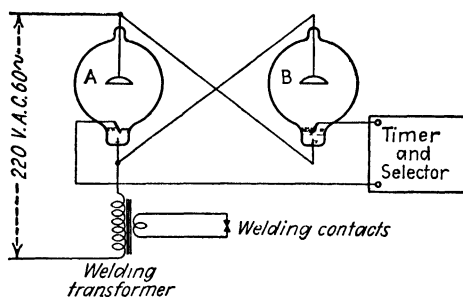
Fig. 13.—Welding circuit using igniter-type tubes.

auxiliary thermionic cathode to the igniter, and at 10 to 20 amp. a cathode spot forms on the mercury, and the arc in the ignitron shorts the thermionic cathode tube out of the circuit. When the main anode becomes negative, no current flows to the igniter, and no cathode spot forms. Thus the current-obstructing property remains unimpaired.
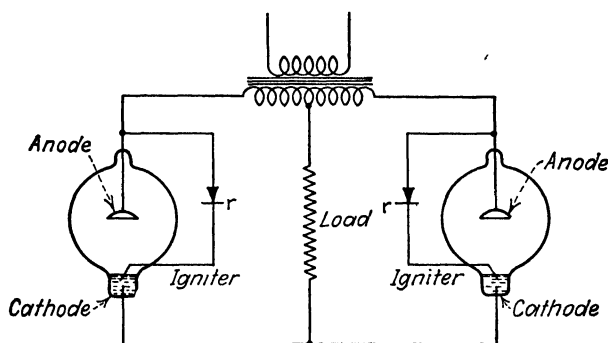
Fig. 14.—Use of rectifiers with igniter-type tubes.

The current carried by the auxiliary thermionic cathode tube need never exceed that sufficient to start a cathode spot upon the mercury. In case of a short circuit in the external circuit, for example, the heavy current is all carried by the ignitron with mercury-pool cathode. The auxiliary tube is then pro-

tected from any severe duty by the ignitron itself, and its life is very long.   At the same time, because of its small size, its renewal is inexpensive.

If the auxiliary thermionic cathode igniter tube is provided with a control grid, then additional possibilities in power conversion become available.   Now, for sending current to the igniter it is necessary not only for the main anode to have the proper positive polarity but also for the grid of the auxiliary thermionic tube to have the proper excitation.   Thus, for example, by retarding the moment of excitation of the igniter, the current-carrying intervals in the circuit of Fig. 14 can be shortened, and the current supplied by the rectifier controllably reduced, with control equipment that needs to handle only the minute currents of the grids of the auxiliary.   This characteristic should be extremely valuable in electrochemical applications.

With control of the grid of the auxiliary thermionic cathode tube, we may not only control rectification or conversion of alternating current into direct current but also effect inversion or conversion of direct current into alternating and also conversion of alternating current of one frequency into that of another frequency.   Circuits for accomplishing these functions are well-known and have frequently been described using discharge tubes with grids interposed between the main electrodes for controlling the initiation of the current-conducting interval.   Clearly, the ignitron with its small grid-controlled auxiliary igniter tube may be used in all these circuits in place of the directly grid-controlled power tubes, with the great advantage that the controlling grid is no longer in the path of the main discharge so that additional loss in efficiency due to the presence of this grid is avoided.

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Methods of Rating Three-element Gaseous Tubes.[1]—Like all electrical and mechanical machines, electron tubes have definite ratings which differ among tubes of a given type. The following ratings and terms relating to grid-controlled rectifiers are in general use:

The *maximum peak inverse voltage* is a rating common to both rectifiers and controlled rectifiers. It is the highest instantaneous voltage that the tube will safely stand in the direction opposite to that in which it is designed to pass current. In other words, it is the safe arc-back limit with the tube operating within the specified temperature range. The relations between the peak inverse voltage, the direct voltage and the r.m.s. value of alternating voltage depend largely upon the individual characteristics of the circuit and the power supply. The presence of line or keying surges, or any other transient or wave form distortion may raise the actual peak voltage to a value which is higher than that calculated from the sine-wave voltages in the transformer. The maximum rating of a tube, therefore, refers to the actual inverse voltage and not to the calculated values. A cathode-ray oscillograph or a spark gap connected across the tube is useful in determining the actual peak inverse voltage. In single-phase circuits, the peak inverse voltage on a rectifier tube for sine-wave conditions is approximately 1.4 times the r.m.s. value of the anode voltage applied to the tube. In polyphase circuits the peak inverse voltage must be determined vectorially. This rating is often abbreviated as M.P.I.V.

[1] PIKE, O. W., and DAYTON ULREY, Ratings of Industrial Electronic Tubes, *Elec. Eng.*, December, 1934, p. 1577.

The *maximum peak forward voltage* applies only to controlled-rectifier types. It is the maximum instantaneous voltage that can be held back by the action of a suitable grid voltage.

The *maximum instantaneous anode current* is the highest instantaneous current that a tube will stand under normal operating conditions in the direction of normal current flow. This applies to both rectifying tubes and grid-controlled rectifiers The length of time which a given tube will stand this instantaneous current, or the frequency with which it will stand an instantaneous current surge of a given duration, depends upon tube heating.

The *maximum surge current* rating is a measure of the ability of a tube to stand extremely high transient currents. This rating is intended to form a basis for set design in limiting the abnormal currents that occur during short-circuit conditions. It does not mean that the tube can be subjected to repeated short-circuits without the probability of a corresponding reduction in life and the possibility of failure.

The *maximum average anode current* is a rating based on tube heating. It is the anode current as measured on a d.c. meter and represents the highest average current which can be carried continuously through the tube. In the case of a rapidly repeating duty cycle, this may be measured on a d.c. meter. Otherwise, it is necessary to calculate the average current over a period not to exceed a definite interval of time which is specified for each design of tube. For instance, a tube with a maximum instantaneous anode current of 15 amp., a maximum average anode current of 2.5 amp., and an integration period of 15 sec. could carry 15 amp. for 2.5 sec. out of each 15 sec., or 7.5 amp. for 5 sec. out of every 15 sec.

The grid-current ratings are given in terms of the *maximum instantaneous grid current* and the *maximum average grid current*, and the integration period is the same as for the plate current.

Cathode Protection.—When a vapor tube[1] of the hot-cathode type is placed in operation by accident or inadvertence before the cathode has reached operating temperature, damage may be done to both the tube and the circuit in which it operates. To prevent this damage, cathodes must have ample heating time

[1] MILES, L. D., and M. M. MORACK, Thermionic Delay Relays for Cathode Protection, *Electronics*, April, 1935.

to insure operating emission current before the tube is placed in service. Accordingly, vapor tubes are given two ratings: an initial preheating period and a reheating period after power interruptions.

It is obvious that the shorter interruptions require less time for reheating owing to the heat storage in the cathode. Protective relay devices should, therefore, be judged by their ability to protect under all operating conditions and by whether they conserve all operating time compatible with safety by appropriate reheating characteristics and by responding to voltage changes.
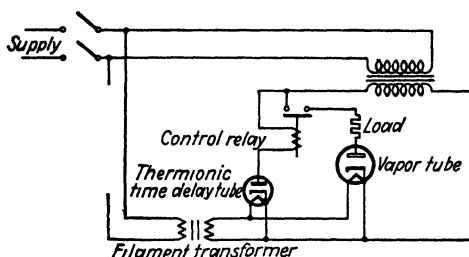
Fig. 15.—Thermionic time-delay relay.

The time delay for heating or reheating must be accomplished by keeping the tube nonconducting either by grid control or by holding the anode circuit open until maximum emission current is available. The former is accomplished by a bias arrangement or a phase-shift scheme, while the latter uses anode contactors operated by a time-delay relay. Time-delay relays used with the preceding methods of control may be classified in the order of increasing desirability as follows:

1. Thermal timers.
2. Mechanical timers.
3. Thermionic timers.

The thermionic time delay is very effective, since it is possible to use a cathode-anode space characteristic similar in heating and cooling to the vapor tube to be protected. The figure, from the reference cited, shows a diode heater shunted across the gas-tube heater and a relay which closes the power to the anode of the gas tube when the diode cathode has reached the proper emission value. A series of diodes has been developed for this protective service.

Lowry[1] has developed a cathode which is self-protecting. The directly heated portion of this cathode is an edge-wound helix, which is closely surrounded by an indirectly heated portion of perforated metal coated only on the inside surface. The discharge is thus forced to pass through the perforations in the screen and then outward through the annular space between the screen and the first radiation shield. This construction has been developed with the object of electrostatically shielding the active surfaces of the cathode to such an extent that they are not subject to high field strengths and are also protected from excessive positive-ion bombardment. These structural features thus lead to a more nearly "foolproof" cathode with much longer life expectancy. In addition, an extremely efficient cathode results.

The current rating of the KU-676 tube using this type of cathode is 6.4 amp. average and 75 amp. crest, while the cathode-heating energy required is only 55 watts.

Controlling the Anode Current.—In a two-element rectifier, anode current flows whenever the anode is positive with respect to the cathode. In the gaseous triode another variable controlling factor enters: the voltage of the grid. Of course, current to the anode can flow only when that anode is positive, but unless the grid has the proper voltage, no current will flow, even if the anode is positive.

There are two general methods of controlling the flow of current in such tubes, an *amplitude* method and a *phase* method. In the amplitude case the voltage applied to the grid is varied until the discharge starts, or with a fixed grid voltage the anode voltage is increased until current flows. The phase method implies the application of alternating current to anode and grid. When the phase between these a.c. voltages is such that the grid of the tube is given the proper critical voltage at some portion of the half cycle during which the anode is positive, current will flow during the remainder of that cycle.

If alternating current is applied to the circuit of Fig. 6 and if the grid voltage is adjusted so that current flows during the entire positive alternation, the tube merely acts as a half-wave rectifier. Since the grid and anode voltage are in phase, both increasing at the same time, it is not possible to cut the flow of current to less than a quarter cycle. If the discharge is not initiated during

[1] Lowry, E. F., *Electronics*, December, 1935.

the first half of the positive alternation, it will not begin at all. Therefore the anode current values are three: (1) no current, caused by the adjustment of the grid voltage too low to start the anode current at the peak value of anode voltage; or (2) current flowing during the entire half cycle; or (3) current flowing for some period between the complete half cycle and one-half this time. That is, the current cannot be adjusted to flow for less than one-quarter of a cycle. So long as the two voltages, anode and grid, are in phase, the above limitation exists. In other words, there is not complete control over the value of average current.

The above method of controlling the flow of current may be termed an *amplitude* method of control. The point in the first half of the positive alternation at which current begins to flow is governed by the adjustment of the grid-voltage slider on the potentiometer so that this voltage bears the required relation to the anode voltage.

The same effect may be secured by using alternating current on both anode and grid but where the frequency of the grid voltage is lower than that of the anode. This method of control is still an amplitude method—if the grid potential is always so low that it does not attain the critical voltage, current will never flow. As soon as the grid voltage is so adjusted that it reaches this critical voltage, the current starts and will continue until the end of the positive half-cycle of anode voltage when the grid will regain control through the de-ionization of the gas and the diffusion of the ions to the walls of the tube. Here again it is impossible to limit the current to a value of less than one-quarter cycle.

By increasing the frequency of the grid voltage the average current may be made to approach a continuous current to any desired degree. The method is essentially one of permitting the current to flow during any desired number of cycles and, depending upon the starting characteristic of the tube, controlling the point in the cycle at which conduction starts.

Control by Direct Current.—Because of the distinct, though small, time required for the ions to diffuse after the discharge has been cut off by shutting off the plate voltage, when the tube is controlled by direct current the plate voltage must not only be reduced to zero but it must be maintained there for a small fraction of a second. This may be accomplished in several ways.

One is by the condenser shown in Fig. 16. When the tube carries current, the drop across it will be of the order of 15 volts. The rest of the line voltage, say 250 volts, is impressed across the resistance R_2. Thus at the terminal of the condenser attached to the anode the voltage is 15, while the other terminal of the condenser is at 250 volts being charged from the line through the
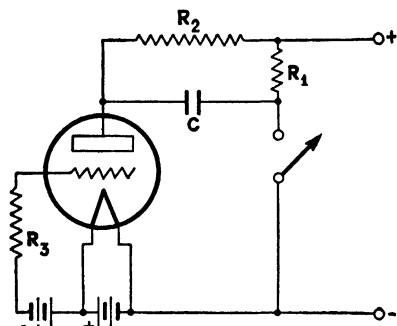
FIG. 16.—Circuit for stopping tube current on direct current by closing switch.

resistance R_1. Now if the switch is closed the 250-volt terminal of the condenser will become 0, and the other terminal will suffer an instantaneous drop in voltage equivalent to $250 - 15$ volts or to the value of minus 235.

Thus the plate becomes negative, the anode current ceases, and the grid has regained control. If the time of de-ionization is less than the time required to recharge the condenser through R_2, the grid has regained control and anode current will not restart.

A Self-stopping Direct-current Circuit.—The circuit[1] of Fig. 16 can be made to start and stop automatically by putting a glow tube across, or in place of, the switch. Then as soon as the condenser potential equals the breakdown potential of the glow tube, the latter becomes conducting and the potential across its terminals drops to very nearly the extinction value. The potential of the anode with respect to the filament is therefore suddenly lowered by an amount approximately equal to the difference between the breakdown and extinction potentials of the glow tube. The condenser discharges until the potential across its terminals equals the extinction voltage of the glow tube and then again starts charging. If the discharge is slow enough to give the rectifier time to de-ionize before the anode again becomes 15 volts positive, then the anode current can be cut off by making the grid sufficiently negative. Just as long as the grid is more positive than the critical control value the only effect of the glow discharge is to cause a periodic instantaneous interruption of load current.

[1] REICH, H. J., *Electronics*, December, 1931.

Since the condenser does not discharge completely, it is necessary to use higher capacity than when a switch is used. The glow tube should have a breakdown voltage which is slightly lower than the load voltage and the extinction potential should be as low as possible. No ballast resistance should be used in series with it. A 10-μf condenser in conjunction with a UX-874 voltage-regulator tube will cut off a 1-amp. current through an FG-67 tube. Greater care in the choice of the glow tube would without doubt make possible the reduction of condenser size.

The average time interval between the setting of the grid voltage and the extinction of the arc is controlled by changing the value of the resistance which may well be the plate resistance of a vacuum tube. If the rectifier grid is made positive for only an instant, it will pass current for a short interval of time whose average length may be adjusted by changing the value of the resistance.

Vacuum-tube Control of Gas Tube.—In many control circuits the action of a variable resistance is desired but the usual types of rheostats, involving sliding contacts and mechanical movement, are not applicable. The ideal type of control device is represented by the vacuum tube in which the plate current may be controlled by the magnitude of the voltage applied to the grid and in which only a negligible amount of power is required to exercise this control. Unfortunately high-vacuum tubes are not available which will furnish the amounts of power (at convenient voltages) frequently required in connection with regulating problems encountered in power engineering. The gas type of tube, on the other hand, has the disadvantage that the anode current cannot be controlled by the magnitude of the grid voltage. Circuits involving combinations of these two types of tubes will furnish the amounts of power (at convenient voltages) frequently required in connection with regulating problems encountered in power engineering. All that is necessary is that variations in a control voltage be made to cause a phase shift of the voltage in one part of an electric circuit with respect to that in another part.

Tube-controlled Circuit.—A second tube may be used instead of the switch of Fig. 16 to force the anode negative. The circuit is in Fig. 17 where the plates are connected to each other by a condenser. To limit the current to the tube, a resistance is in

series with each anode and the line. Suppose one of the tubes to be conducting and the other idle. The voltage of the anode of the conducting tube is 15 while that of the other tube is 250. Now if the nonconducting tube grid is raised to the point at which current flows, its anode voltage drops from 250 to 15 volts, a drop of 235 volts. The anode voltage of the first tube must fall an equal amount since they are connected together by a condenser which cannot discharge instantaneously. Thus the first anode is reduced from 15 to −220 and the flow of current ceases.

Fig. 17.—Circuit in which one tube controls another.

If the time constant of the condenser circuit is high enough to prevent the voltage across the condenser to rise to the value at which the first anode will be positive until the ions have time to diffuse, the grid of the first tube has control and current will not flow. In this process the discharge shifts from the first to the second tube. The grid voltage may be impressed by a transformer as shown in the figure, or in any other desirable way. A most important application is derived from this circuit by using one winding of a transformer instead of the plate resistances to limit the rate of charge of the anode condenser. Across the secondary of this transformer will be alternating voltages because of the shift of discharge from one tube to the other and of course this alternating current can be used for any desired purpose.

This is the function of *inversion*, the conversion of direct current into alternating current, described on page 231 *et seq.*

Phase Control of Anode Current.—A more elegant method of controlling the average current consists in varying the phase between the grid and anode voltages. This method determines how much current is permitted to flow in each cycle. The method of control is shown in Fig. 18. Here E_p is the anode

potential, assumed to be a sine wave, and E_g the grid bias, positive above and negative below the line, that will just allow the tube to fire at the corresponding value of E_p. V_g is a sine wave of grid voltage (V_g need not be a sine wave or of the same frequency as E_p). Consider that this wave be moved along the horizontal axis so that it may be moved into or out of phase with E_p. The tube will fire at the earliest point in the cycle at which V_g crosses E_g; in the figure, point P. When the grid and anode voltages are out of

FIG. 18.—Phase control of gas tube.

phase, no current flows. If the grid voltage is advanced, current flows during part of the cycle, and by advancing the grid voltage until it is in phase with the anode voltage the

$$E_{DC} = \frac{E_m}{\pi}(1+\cos\phi) \text{ or } E_{DC} = \frac{E_m}{\pi} K$$

Angle-ϕ

= Rectified output

Averaged output = as a function of phase angle

I Ave.

Phase Angle Advance
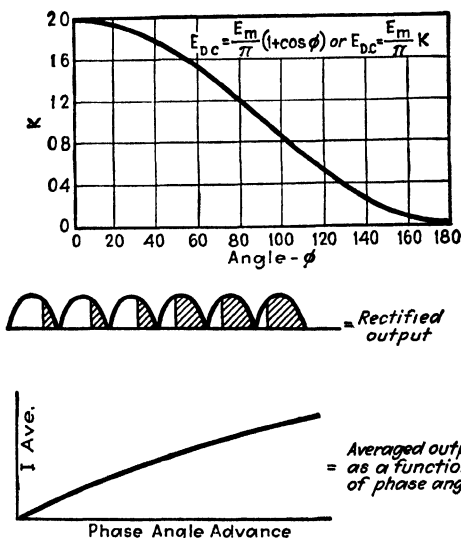
Fig. 19.—Average current as a function of point in cycle (ϕ) at which tube fires.

current can be made to flow during the entire half cycle. The methods by which the variation in phase is effected are described on page 192 *et seq.*

The average current flowing may be found from the expression

$$I_{ave} = I_{crest}\left(\frac{1 + \cos \phi}{\pi}\right),$$

where ϕ = angle at which tube starts to conduct current.
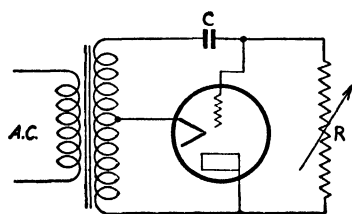
Fig. 20.—Phase control circuit.

Circuits for Obtaining Phase Control.—There are many ways of obtaining phase shift between anode and grid voltages. The combinations of resistance and capacity, or of resistance and inductance, are legion. For example, in Fig. 20 a combination of resistance and capacity is used. The filament, grid, and anode voltages are all obtained from a transformer. The grid connection being at the opposite end of the transformer winding
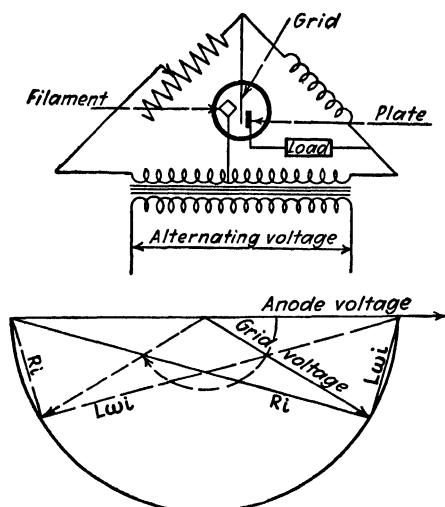
Fig. 21.—Circuit and phase relations in resistance-inductance control of tube. If R the resistance is large, grid and anode voltages are nearly in phase and a greater average current will flow.

from the anode has an opposite polarity with respect to the filament. Thus when the anode is positive, the grid is negative. This need not be the case, of course. The grid can be maintained positive with respect to the cathode if desired.

The voltages across the condenser and the resistor are 90 deg. apart. Combining them vectorially gives the total voltage appearing across the transformer winding. By making R very large, the phase difference between the grid and the anode is great with consequent decrease in the time per cycle the tube conducts; by making R equal to zero, the grid and anode become in phase and the tube will conduct current throughout the positive half cycle.

A circuit in which an inductor and a variable resistor are used and the corresponding relations between the grid and anode voltages are shown in Fig. 21.

In both of these circuits the varying degrees of control are secured by changing a resistance. Of course, this change can be accomplished manually as by turning a dial on a resistor (as in illumination control) or automatically by any varying process, function, or moving part, or it may be effected by the varying resistance of a light-sensitive cell under different intensities of illumination.

Fig. 22.—Varying resistance of phototube changes phase between grid and anode.

Use of Photocell.—For example, in Fig. 22 is a photocell between grid and plate. Here the varying control is made possible by the varying rate at which the condenser is charged through the photocell. The charge current through the tube varies continuously and uniformly as the illumination is varied.

Many quantitative data on methods of control and other information resulting from an extended laboratory investigation on gas triodes will be found in Characteristics of Small Grid-controlled Hot-cathode Mercury Arcs or Thyratrons, by W. B. Nottingham, *J. Franklin Inst.*, March, 1931, p. 271.

In Fig. 24 R and C_1 form a phase-shifting bridge giving a voltage wave e_1 which is adjustable with reference to the anode voltage e_a. During positive half cycles of e_1 a charge is drawn to the grid side of C_g through the cathode-grid circuit, the opposite and approximately equal condenser voltage being represented by a wave e_c. As e_c falls off from its peak value (due to the discharge of C_g through the phototube), a point is reached at which e_c can no longer reduce as rapidly as e_1 because C_g cannot

discharge back through the cathode-grid circuit and can discharge only through the phototube. Up to this point the grid is at approximately cathode potential (slightly higher during the
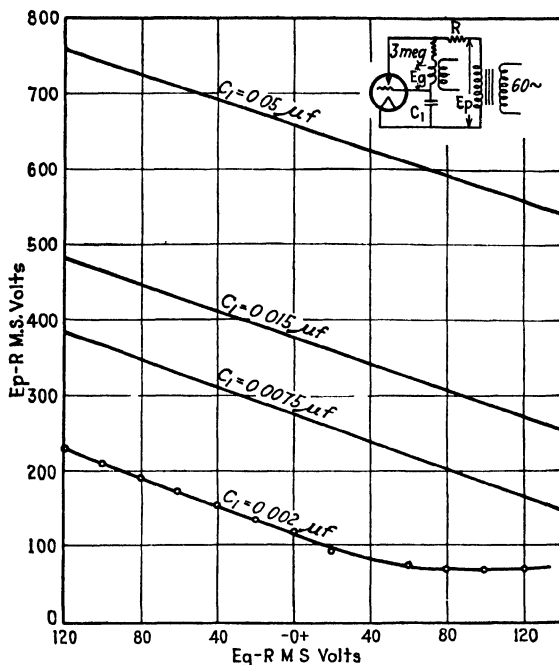
Fig. 23.—Variation of control as function of capacity between grid and cathode.

process of charging C_g), but beyond this point has a greater absolute value than e_1 so that there is a net negative potential
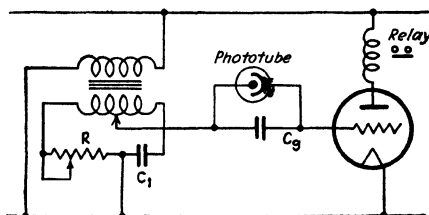
Fig. 24.—Stable control by phototube of gas-tube output.

on the grid. The variation of current through the phototube varies the phase in the circuit. This method gives stable control of a mercury tube by phototube.

Figure 25[1] shows a phase-control element in which the tube plate current is controlled by the phase relation between the voltage and current in a circuit. If the power factor is zero, there is no resultant plate current; if the power factor changes from leading to lagging, the plate current reverses accordingly. The grid excitation is of the same polarity for both tubes, but the plates are excited in opposition. Thus with this arrangement the voltage across the resistance is zero when the power factor is zero, is positive when the power is positive and negative when the power reverses. It can be used in a similar way to indicate the phase relation of any two voltages. The voltage across the
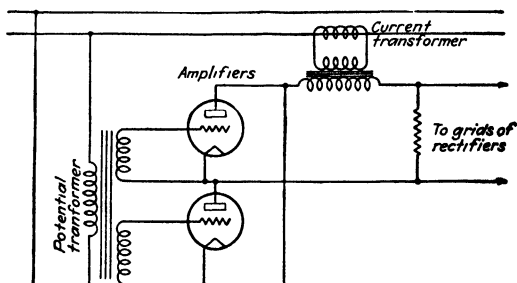
Fig. 25.—Phase control by amplifier tubes.

resistance may be used to control the grids of additional vacuum tubes.

Current Control by Transformer and Phase Shift.—The circuit and curve in Fig. 25A show an example of the ability of the controlled rectifier to pass more or less average current to a load by means of a phase-shift circuit (resistance and inductance), by changing the impedance of a transformer in series with the load.

Bridge-circuit Phase Control.—The phase relation between grid and plate may be controlled by a bridge incorporating resistances, or resistance and reactance. If the resistance or the reactance is varied, the grid phase will shift, and control will be obtained. One such system of control uses for the reactance a small solenoid with a movable core. When the free-hanging solenoid is raised or lowered, the grid phase is shifted and the tube output is varied accordingly. In another type, a resistance

[1] BAKER, FITZGERALD, and WHITNEY, Industrial Uses of Electron Tubes, *Electronics*, January, 1931; April, 1931.

is varied by making one side of the bridge a resistance ther-
mometer thereby providing heat regulation.   Another form uses
a stack of carbon disks under variable pressure.   A movement
of one hundred thousandth of an inch serves to actuate the
system.

In Fig. 26 the triodes are used as a variable impedance, and
although they are undirectional in their effect, by means of a
combination of two triodes and a transformer, an effective a.c.
impedance is obtained which varies with the current taken by the
triodes.   This variation in impedance unbalances the bridge,
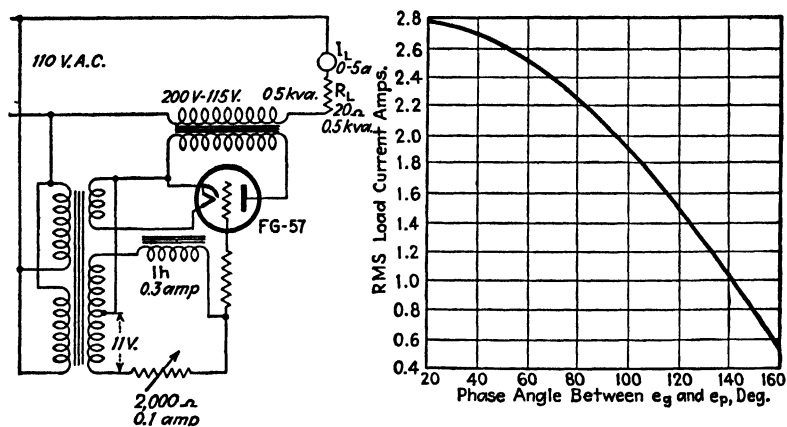
Fig. 25A.—Magnitude of control effected by gas tube.

and the unbalance voltage is impressed on the gas-tube grid.
By these means, variations in the grid bias of the vacuum tubes
will produce a variation in the circuit impedance and a shift in
the phase of the voltage across the network.   By applying a
suitable voltage to the grids of the vacuum tubes the phase
relation of the rectifier may be varied over a sufficient range to
control completely the anode current.   The effect gained when
an a.c. plate voltage is used is exactly the same as if we had a
vacuum tube capable of handling, at moderate voltages, the
heavy currents associated with the use of gas tubes.

Methods of Controlling Output.—The grid-controlled rectifier
will take power from alternating current and deliver it at direct
current in desired amounts to loads of various sorts.   For exam-
ple Fig. 27 showing a circuit adapted to theater-stage-lighting
control, as well as control of d.c. motors, furnishes a full-wave

rectified current, the magnitude of which can be controlled by the angular setting of the phase-shifter rotor. The power output
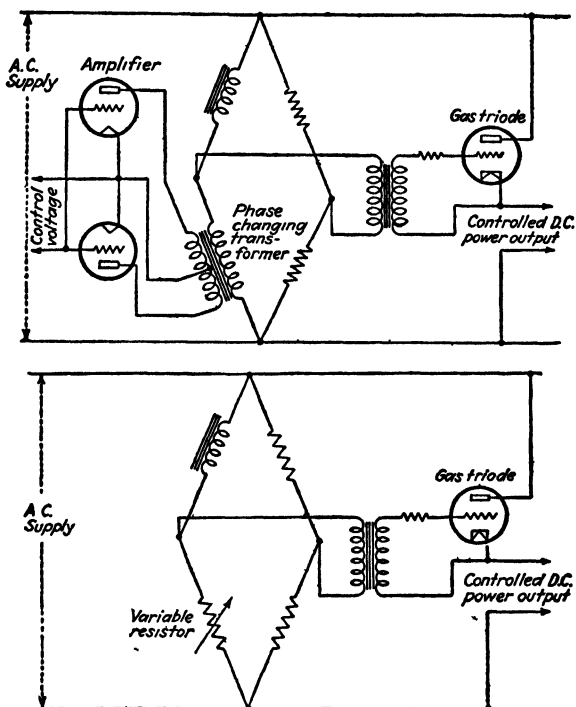
FIG. 26.—Bridge circuits for effecting phase control.
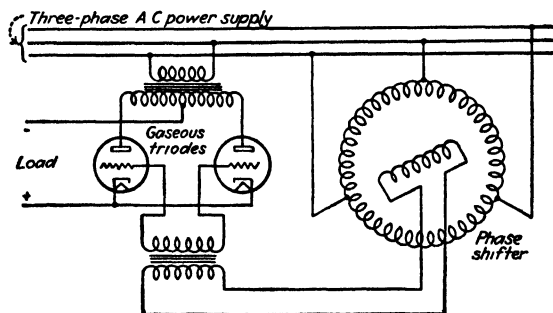
FIG. 27.—Controlled-rectifier circuit supplying variable d.c power from a.c. source.

of the rectifier can be varied from full load to zero in a fraction of a revolution of the rotor as determined by the number of poles on the phase shifter.

The circuit shown in Fig. 28 is much the same as that of Fig. 27 except that the control is obtained by means of a variable resistance. A capacitor and resistor are connected in series across the supply voltage and the voltage across the capacitor is applied to the tube grids. This voltage is in phase with the supply voltage if the resistance is zero and lags the supply voltage as the resistance is increased, up to a theoretical value of 90 deg. In practice this range is not entirely available, since for high values of resistance the voltage across the capacitor becomes reduced in magnitude. Manual control of the tube current can be obtained by using a rheostat for this purpose, but the
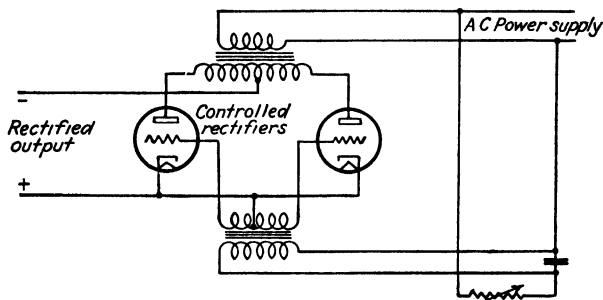
Fig. 28.—Variable resistance method of control producing variation in phase between resistance and capacity voltages.

more valuable feature of resistance control resides in the possibilities which it provides of obtaining control by means not involving mechanical movement. Thus the tube current can be controlled by any effect which can change resistance, for example, photo-electric action, thermal effects, or additional electron tubes.

Magnetic Control.[1]—Experiments with two electrode tubes have shown that a transverse magnetic field will deflect the electrons emerging from the cathode away from a direct line to the anode but ordinarily will not prevent breakdown. The reason for this is that the insulating tube walls build up a large negative charge which deflects the incident electrons. The electrons move along the wall until they reach the region of strong field near the anode and cause an arc discharge to start.

These considerations suggest the design principles for a magnetically controlled tube. In general, these requirements are:

[1] McArthur, E. D., *Electronics*, January, 1935, p. 12.

1. A large volume for a deflection chamber.
2. Sufficient shielding so that the electric field in the chamber is low.
3. Conducting walls for the chamber.
4. A chamber at least partially bounded by the cathode structure.

Use of Controlled Rectifiers as Switches.—The simplest and one of the most important functions of the gas tubes under

$E_f = 5.0 \ v.$
$E_s = 127.0 \ v.$
A.C. Field 16.0 Gauss

Average Anode Current Amperes

D.C. Field Strength—Gauss
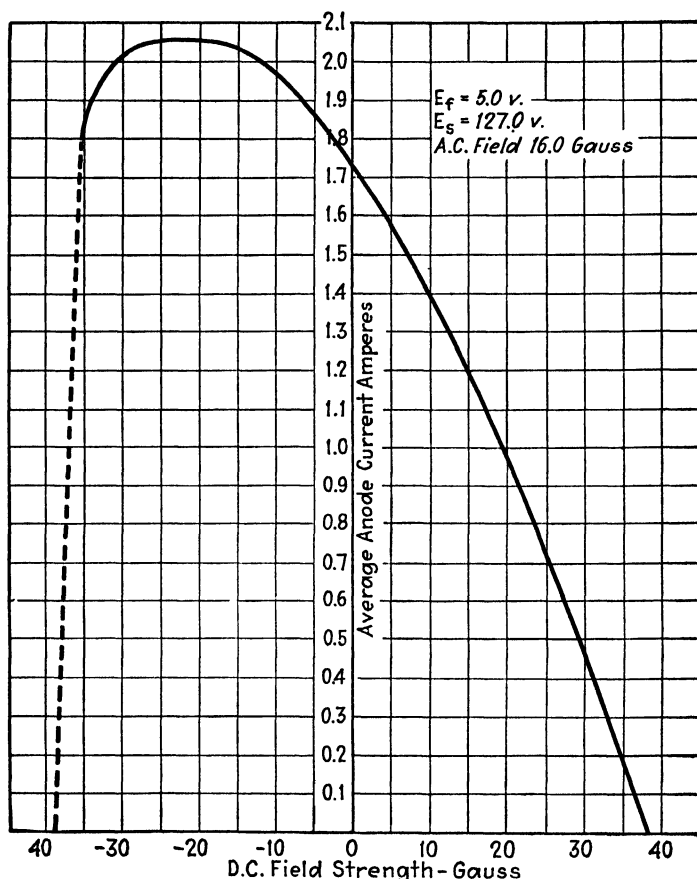
Fig. 29.—Typical characteristic of tube controlled by magnetic field.

description is that of simple switches, turning current on and off. Compared to an ordinary switch or contactor the tube has greater sensitiveness, *i.e.*, it will control a given amount of power with a smaller expenditure of power; it has greater speed; almost total absence of wear (the tube may have a life upwards of 10,000

hours in continuous service); it is quiet in operation.   A typical
circuit is given in Fig. 30 where the controlling element may
be a manually operated switch, a clock, thermostat, or a photo-
tube.   The load may be for either direct or alternating current.
The control voltage is shown as direct voltage, but usually it is
an alternating voltage.   The bias voltage is usually from rectified
alternating current obtained from a copper oxide rectifier.

Such a circuit may be used to control motors, magnets, con-
tactors, or to saturate the core of a reactor as in illumination or
welding control.   Applications such as turning on lights at dusk
by a phototube and off again at sunrise, cutting hot steel bars to
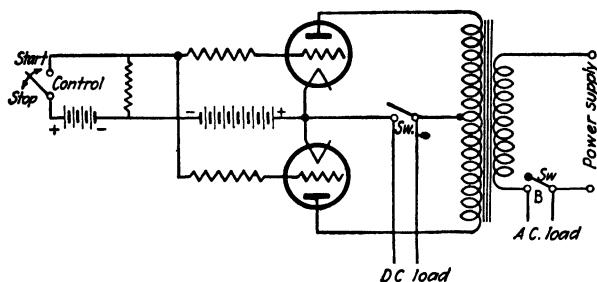
Fig. 30.—Controlled rectifiers used as power switches.

desired lengths, opening doors at the approach of a person,
wrapping packages, dispatching products to predetermined
stations, sorting objects, counting—all these applications and
many others are in daily use.

When the load is in the alternating-current output, for example,
in welding, and when the tubes are not conducting, the trans-
former has a high impedance, and little current will flow into the
a.c. load.   When the tubes take current, this impedance decreases
so that full power will flow into the load.

Figure 31 shows a d.c. circuit using two gaseous triodes, one to
energize the circuit and the other to de-energize it.   The upper
tube with the condenser shunted by a resistor carries only a
transient current which interrupts momentarily the current in
the second tube so that its grid gets control.   This condenser-
resistance circuit will be found in many vacuum- and gas-tube
circuits.   It is a most useful tool.

Controlled Rectifiers as Relays.—A good discussion of this
subject will be found in *Electrical Engineering*, October, 1934, by

Rolf Wideroe, who explains the analogy between certain mechanical and tube relay systems.   He starts with a simple overload and underload relay, showing how a tube may be used in place of a mechanical circuit breaker.   The first, naturally, consists of a rectifier whose grid permits the flow of current when a certain voltage is reached.   The next step, toward making an undervoltage relay, is to rectify the voltage to be controlled, using it to overcome a positive bias put on the grid from a battery or other source.   When the voltage falls too low, the bias battery will permit the tube to fire.
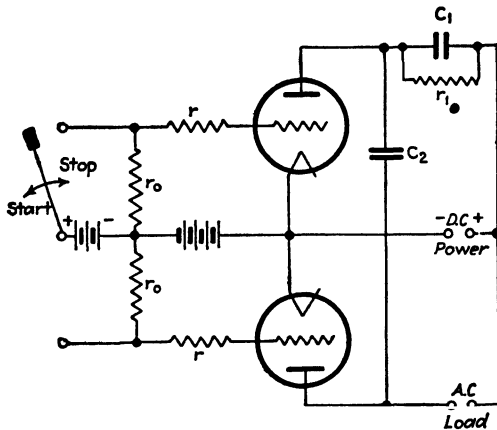
FIG. 31.—Use of one tube to stop and another to start flow of power.

By combining the over- and undervoltage relays, a percentage differential relay or an underimpedance relay may be made. Still other more complex circuits are given in this reference.

Wideroe discusses the effects of disturbances and temperature upon such relays, noting that the mercury-vapor tubes will be at a disadvantage in such circuits because of their temperature characteristics.   He states, however, that argon-filled tubes have fired at a grid voltage within approximately 0.2 volt over a long period and that varying the anode potential by 10 per cent will not cause a variation of more than plus or minus 5 per cent in the firing grid voltage.

A Vacuum-tube Time Switch.—A fundamental tool is the condenser shunted by a resistance.   The time constant of such a circuit is a function of the value of the capacity and the value of the resistance; thus, the time constant is CR.   This means simply

that the time to charge and discharge is controlled by this term. (Actually this product gives the time for the charge to fall to 37 per cent of its former value.) If the shunted condenser is properly connected to the grid of a tube so that the voltage across the condenser is the voltage between grid and cathode, the plate current of that tube can be permitted to flow, or prevented, for any desired interval.

Such a switch[1] has been used for a number of purposes (in welding, for example). One such vacuum-tube time switch is
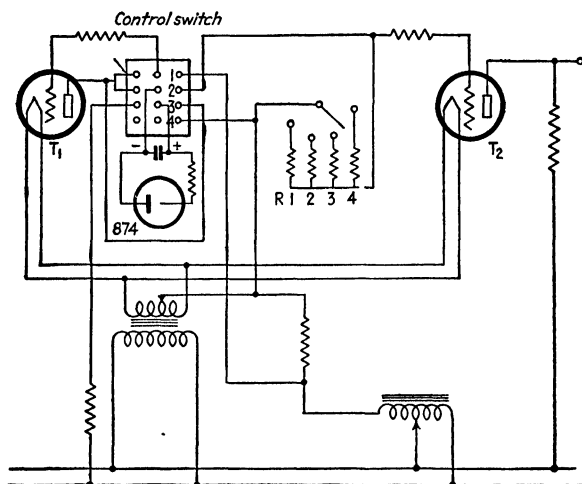
FIG. 32.—Time switch utilizing two triodes and one diode, all gas tubes.

illustrated in Fig. 32. Here a grid-controlled rectifier charges the condenser, the terminals of which are thereby raised in voltage sufficient to prevent the flow of anode current in a second rectifier. The time required for the condenser charge to leak off through one of the resistors R_1, R_2, R_3, or R_4, governs the time required for the voltage across the condenser to fall to a value low enough for the grid to lose control of the anode current. The second grid-controlled tube can control a relay or another tube as desired.

In this circuit a hand-operated switch is used to cause the condenser to charge or to discharge. A glow tube (UX-874)

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[1] KEARSLEY, W. K., A Vacuum-tube Time Switch, *Gen. Elec. Rev.*, February, 1931. A more recent time switch using a controlled rectifier for welding applications will be found on p. 258.

is used across the condenser to keep the voltage across it from rising above 90 volts. To improve the accuracy of timing, the switch is arranged so that the first blade to make contact (blade 1) connects the grid of T_1 to a point in the circuit which is negative whenever current flows in T_2. The condenser must discharge through T_1 before it can bias the tube of T_2. Regardless of the point in the cycle at which the switch is closed, the condenser will not discharge until a negative half-wave is present. Blade 4
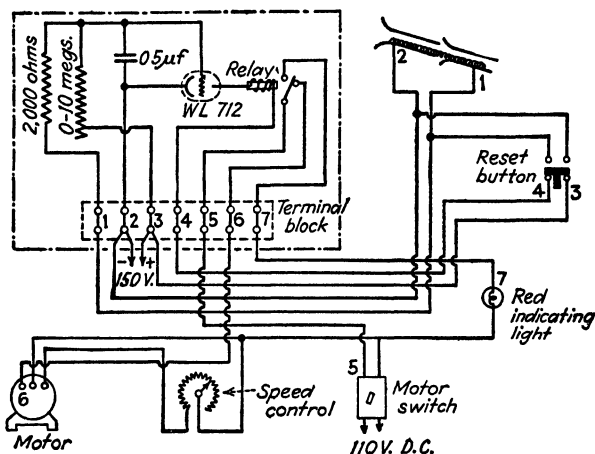
FIG. 33.—Filament coils passing through funnel· (1–2) maintain 0.5μf condenser discharged. If filaments do not arrive at funnel, condenser voltage stops filament machine through gas tube WL-712.

engages last and short-circuits T_1 leaving the condenser connected to T_2.

With 8 μf and 750,000 ohms the time of control is 20 sec. The time can be set as low as one-half cycle. The accuracy is such that, set for 1/10 sec., the circuit will remain closed for six current impulses 90 per cent of the time. Occasionally it will remain closed for 7 half-cycles. With a 20-sec. period, the error may be 1 sec.

Time–delay Relays.—The application of a condenser charged through a resistor has been made use of in automatically stopping a mandrelless filament coil-making machine in the Westinghouse Lamp Company.[1] In these machines the filament wire is projected against a diamond die so that upon deflection it forms helical-coiled filaments hair-like in dimensions. These filaments

[1] HOLLOWAY, G. C., *Electronics*, August, 1933, p. 220.

are cut off at the rate of approximately 80 per minute in lengths of a few inches. The coils pass through two funnel-shaped contacts insulated from each other and in series with a 2,000-ohm resistor which is shunted across the condenser ($0.5\mu f$) and forms the time-delay circuit.

When, for any reason, a filament coil is not produced for any pre-set time, the voltage builds up across the condenser and finally
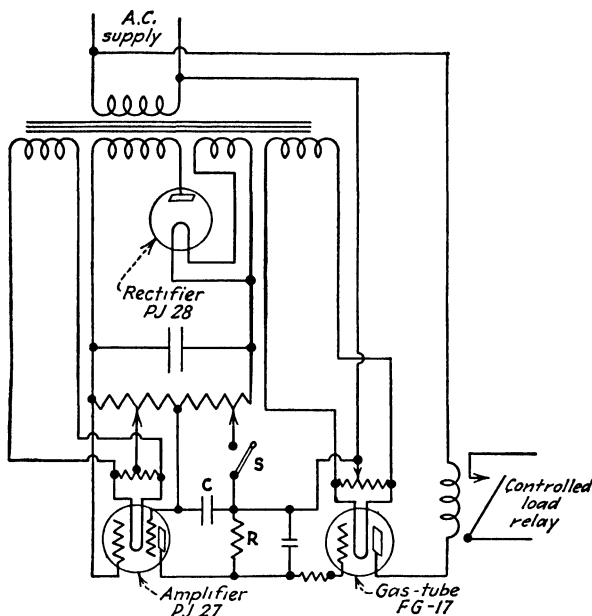
Fig. 34.—Time-delay circuit using screen-grid amplifier tube and gas tube.

reaches the critical value to start a discharge through a cold-cathode glow tube (WL-712). The machine is stopped and an indicating lamp is lighted to attract the attention of the operator.

The reduction in shrinkage and loss of material and time by the use of the simple system has made it possible to write off the cost of the installation in six months.

Another time-delay circuit[1] is shown in Fig. 34. It will give a definite time-delay device to operate over a time range of 30 minutes. To obtain the desired characteristic, the four-element vacuum tube was brought into use. The plate current of a screen-grid tube is practically independent of plate voltage;

[1] BAKER, FITZGERALD, and WHITNEY, *Electronics*, April, 1931.

it is determined by the voltages on the control and screen grids as long as the plate voltage is above the screen voltage. As the plate voltage is reduced below the screen voltage, the plate current falls off rapidly.

The circuit in Fig. 34 utilizes this characteristic. The a.c. supply is rectified and divided by the potentiometer to give the proper voltages on the two grids, and the remainder is applied to the capacitor C. When switch S is opened, the capacitor C discharges at a constant rate through resistor R and the plate-filament circuit of the screen grid. The discharge current gives
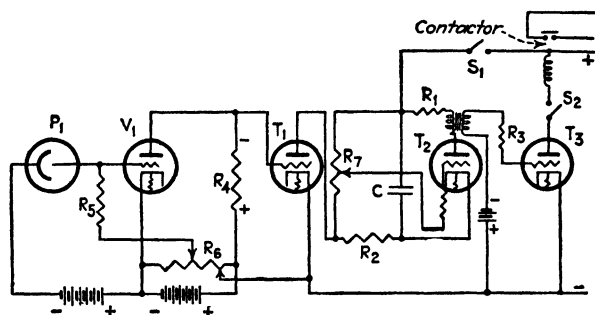
Fig. 35.—Relay in which an impulse may operate a relay a definite time after the impulse.

a drop across R which controls the tube. The time is directly proportional to the voltage to which the capacitor is charged and the value of the capacity.

The time delay between the opening of the switch S and the operation of the tube is directly proportional to the voltage to which the capacitor is charged and the value of the capacity.

The time delay between the opening of the switch S and the operation of the tube is directly proportional to the charging voltage applied to the capacitor. The obvious way to control the timing is by means of a potentiometer controlling this voltage. The potentiometer may then be calibrated directly in time. The time error with voltage change is very small over a given range.

Time-delay Relay.—Figure 35 makes use of a nonrecurring type of operating cycle. If the switch S_1 is closed, at a definite time later the tube will conduct, making it possible to operate some further device at a definite time after the initial movement

which closes the switch S_1.   By changing the values of R_2 and C, this time may be readily changed from a fraction of a second to 10 min. or longer.

If the grid lead is returned to the negative line through a small negative bias, the tube will never fire unless an additional signal impulse of positive nature is inserted in series with the grid circuit.   This then forms an impulse amplifier in which a weak impulse trips the circuit, giving a powerful impulse whose magnitude and shape are independent of the tripping impulse.   This is
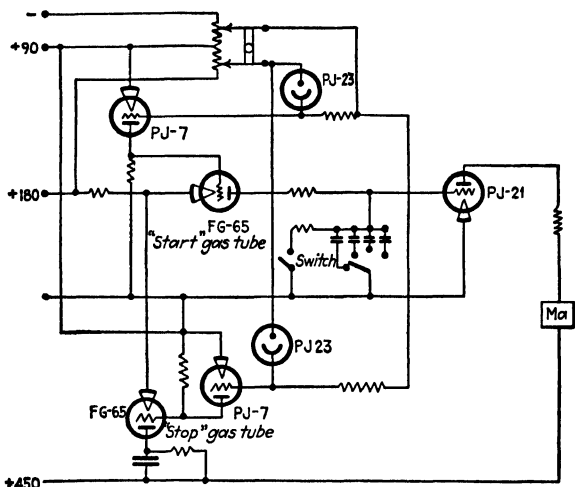
Fig. 36.—Circuit for timing intervals in a range between 0.5 to 0.005 sec.

one scheme of providing a peaked grid excitation for large power grid-controlled rectifiers in multitube circuits where conduction angles are short and the "firing point" must be accurately determined.

Measuring Small Time Intervals.[1]—A circuit for timing intervals shorter than stop-watch periods is shown in Fig. 36 and an instrument has been built using this new circuit, which covers a range of 0.5 to 0.005 sec. in four scale ranges.

The basic idea of the timer includes one gas triode tube, tripped by the starting impulse, to initiate the circuit timing, and a second tube, tripped by the finishing impulse, to stop the circuit timing, the time between impulses registering on an ordinary milliammeter in the plate circuit of a vacuum tube,

[1] LORD, H. W., *Electronics*, October, 1932.

the grid voltage of which is a function of the time between impulses. The elapsed time in seconds between the two impulses is obtained by a calibration curve with "seconds" and "milliamperes" as coordinates. Different scale ranges are obtained by changing the constants of the timing circuit. The arrangement is entirely electrical involving no mechanical elements or moving parts, using the familiar condenser-resistance combination often found in electron-tube circuits.

A timer using the interruption of a pair of light beams as sources of the "start" and "finish" impulses has been developed. An electrical impulse produced in the output of the phototube by interruption of the light falling on it is amplified by a vacuum-tube amplifier to obtain sufficient voltage swing to trip the grid-controlled rectifier. Additional sensitivity to very slender objects is obtained by bringing the light beams to a sharp focus approximately midway between the light sources and the phototubes. The "start" gaseous tube with its phototube, amplifier, and light source is built in a box separate from the remainder of the apparatus. Power is supplied to this box through plug-in cables which may be as much as 20 ft. long when using the longer time scales. Particular interest has been shown in the use of this instrument to measure the speed of a golf-club head as it strikes a ball.

Other uses have been suggested such as measuring the speeds of pitched baseballs, golf balls, automobiles on the road, and projectiles in flight.

Applications of Controlled Rectifiers.—Considering that these tubes are electrical contactors which close instantly, in which the current to a load not only can be turned on or off, but whose average value over any interval of time can be varied from zero to a maximum value, which suffer not at all from one of the troubles that beset a mechanical relay—sparking contacts, sticking, heating, etc.—considering all the advantages plus the feature that tubes of this nature have been built which will deliver 15,000 volts alternating current at 64 amp., it is not difficult to see that the possible applications of the controlled rectifier are legion.

While it is true that ways are found to improve older processes each time an electron tube makes simpler or more satisfactory a process now accomplished or controlled by mechanical or other

electrical means, yet the tube has plenty of opportunity in new processes not now accomplished by other means. Whether the future will see the tube displacing other types of control mechanisms is difficult to state; and indeed it is unnecessary to conjecture on this point. As knowledge of the various tubes increases, new uses will be found for them. The electron tube will become another electrical tool of vast importance.

"In many applications the photo tube acts as the brains, giving orders, in the form of grid voltage to its power team mate, the thyratron tube."[1]

For example, a package wrapping machine cuts off the printed wrappers from a roll, hence any tendency to creep would soon bring the cut through the printing instead of through the interspace where it belongs. A spot is printed in this space which is scanned by a photo-electric cell. Every time it sees a spot before its eye, it operates through a gaseous triode a relay which causes the machine to chop the wrapper. The machine wraps 72 packages of cereals per minute so the total cycle of action from eye to chopper is almost instantaneous.

Another application starting with light control has to do with pipe finishing. Oil-pipe-line pipe is finished true and beveled on each end for welding. The work is done in a center-chuck machine in which pipes of varying length are chucked only approximately by the middle. Two tool carriers run in at high speed until they are $\frac{1}{8}$ in. from the end of the pipe when they suddenly slow down to the cutting speed. There are no dogs, cams, or other mechanical gadgets used on these machines, for the pipe breaks a beam of light that is riding with the tool carrier. By way of controlled rectifiers, the motor control is shifted from high speed to cutting speed when the light is interrupted. There is thus no wear, noise or adjustment involved.

A multitude of practical applications of these tubes have been made in industries that are not given to fancy devices. They serve alongside the heaviest machinery. In the rolling mill, they control the scaling water to hot blooms; in the foundry they stop great flasks within a quarter inch of the pouring spot, in the chemical plant they control intricate processes. They

[1] HULL, A. W., *Gen. Elec. Rev.*, December, 1932, p. 628.

work with electric micrometer gages that move a pointer 5 in. for a half mil error. They hold humidity constant for the printer and textile manufacturer and they add their heavy effort to the tiny nerve impulse of the phototube to hold material in line, to open doors, to control baking, to detect smoke, to turn on and off street lights, signs and factory lights, to count automobiles, theater patrons, refrigerators coming from the production line. They open doors at the approach of a waitress in a restaurant or at the approach of a truck in a factory; pile bags and other production articles, convey products from one place to other predetermined destinations, dispatch mail and parcels; turn on and off lights in response to daylight conditions; cut white-hot steel bars to exact length; fold paper napkins; they sort beans at the rate of 40,000 lb. per day, automatically throwing out all that are imperfect or discolored.

Industrial Applications of Gaseous Triodes.—The largest field of application of these electron tubes at the present time is as power amplifiers for controlling mechanical operation. For this purpose the anode is fed with a.c. power, the grids are actuated from either direct or alternating current depending upon the type of service required.

When alternating voltage is used for the grid, if the grid voltage is in phase with the anode voltage, the current starts at the beginning of every cycle, as soon as the anode voltage becomes positive, and stops at the end of the half cycle when the anode voltage reverses. These half-cycle pulses of current are full value, limited only by the load resistance. If the grid voltage becomes positive 90 deg., or $\frac{1}{4}$ cycle, later than the anode voltage, the current starts at the middle of each cycle and has only $\frac{1}{4}$ cycle to flow. The average value of these quarter-cycle pulses of current is obviously only half as great as that of the half-cycle pulses. If the phase of the grid voltage is still further retarded, the pulses become shorter and shorter, reaching zero when the grid voltage lags 180 deg. behind the anode voltage. Thus by varying the *phase* of the grid voltage one obtains a smooth variation of *average* current, from maximum value to zero.

Circuits of various types or services are given below as typical examples of the versatility of the controlled-rectifier type of electron tube.

Gas-tube Voltmeter.—A method using a gaseous triode for measuring small a.c. voltages has been described by Hughes.[1] This makes use of the fact that the characteristic of such a tube, *i.e.*, the relation between grid voltage and plate voltage for current to flow, is very steep. The voltage to be measured is added to a fixed grid bias which is then reduced until the tube fires. The circuit in Fig. 37 shows the arrangement for determining the peak value of an alternating current such as the magnetizing current of a transformer *T*. The alternating
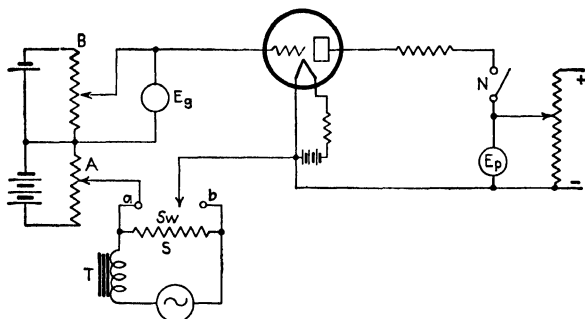
Fig. 37.—Peak voltmeter using gaseous triode.

current is passed through a standard shunt *S*; and by means of a two-way switch *Sw*, the alternating potential difference can be applied to the grid. The function of potentiometer *A* is to give a constant negative bias, such that when *Sw* is on *a*, only a very small extra bias is required from another potentiometer *B* to prevent the anode glow appearing in the tube.

The test procedure is as follows: with switch *N* open, E_p is adjusted to, say, 100 volts and the grid bias of *B* is made greater than the critical value. *N* is then closed and *B* reduced until the tube suddenly glows. The reading on E_g just before the appearance of the glow is noted. Once the ionization has commenced, positive ions are attracted to the grid, and consequently there is a decrease in the reading on E_g. The critical voltage on *B* may be checked, however, by opening *N*, thereby eliminating the grid current.

[1] HUGHES, EDWARD, The Measurement of Peak Values of Alternating Currents and Voltages by Means of a Thyratron, *J. Sci. Instruments*, June, 1933.

Switch *Sw* is next moved over to *b* and the test repeated. The difference between the readings on E_g with *Sw* on *a* and *b*, respectively, gives the maximum potential difference across *S*.

The author has used this method with satisfaction for frequencies varying from 20 to 500 cycles per second. With a low-reading voltmeter for E_g, it is possible to determine the critical grid voltage within 0.01 volt.

The method has been mainly used for measurement of the potential drop across a standard shunt; this did not exceed 2 volts, and could be determined within 0.02 volt. There appears to be no reason, however, why the same method should not be applied to determine: (*a*) The maximum value of much larger alternating voltages either directly or indirectly by connecting two unequal condensers in series and measuring the maximum potential difference across the larger unit; (*b*) The maximum value of a current of any magnitude in a high-voltage circuit by means of a current transformer having the standard 5VA secondary loaded on a noninductive resistance of about one ohm. With only a 5VA load on a standard transformer, it has been found that even for very distorted wave forms, the shapes of the primary and secondary currents are practically identical. Hence the maximum value of the primary current can be determined by substituting the secondary load of the current transformer for *S* in circuit diagram.

Ruiz[1] uses an argon-filled tube, the FG-81, because the conditions of anode and grid voltage for which the tube fires are reproducible within fairly close limits.

Capacity-operated Relay.—A simple circuit using a shield-grid controlled rectifier is shown in Fig. 38. The metal plate should be of the order of 8 by 10 in. When it is approached, the tube conducts, ringing an alarm, for example. The capacity should be adjusted until the tube does not conduct until the hand, or other object, is brought near the metal plate. The wiring attached to the control grid should be as short as possible. Reversing the power plug may make the circuit operate better,

[1] Ruiz, J. J., *Rev. Sci. Instruments*, June, 1935. See also H. W. Lord and O. W. Livingston, *Electronics*, September, 1936, on the use of a grid controlled rectifier or a voltmeter used to determine the end-of-life of similar rectifiers.

since that changes the point of grounding the circuit (see also Chap. VII).

Watch-tick Amplifier.—Many attempts have been made to use electronic circuits for the rapid regulation of watches. A
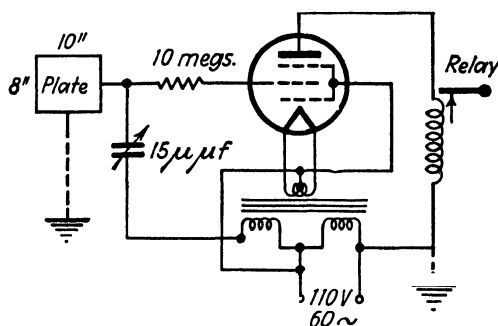
Fig. 38.—Capacity-operated relay.

chronograph system, making use of the technique of facsimile or picture transmission, has been developed by Charles J. Young and Maurice Artzt,[1] of RCA Manufacturing Company, into a
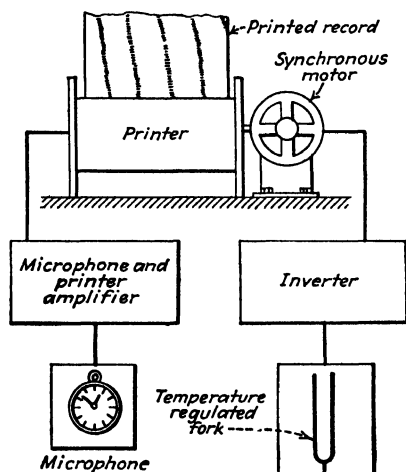
Fig. 39.—Details of watch timer.

watch-analyzing mechanism which checks timepieces and automatically prints a case-history picture of any trouble. By this means the time-keeping capacity of a watch, to an accuracy of within 1 sec. a day, can be determined in 1 min. The device uses

[1] *Electronics*, July, 1935, p. 220.

a tuning fork, accurately temperature controlled, as a time-frequency standard. The fork controls the speed of a driving motor which rotates the paper on which the record is to be kept. The watch ticks are amplified after being picked up by a microphone. The amplified ticks operate a printer recorder mechanism which makes marks on the recording paper. An error of one part in a million may be recorded and measured in about 1 min. of testing.

Measuring Commutator Roughness.—An interesting application of the grid-controlled rectifier has been made by A. M. Harrison of Westinghouse. This is the measurement of commutator roughness by determining the voltage variations when current is passed through a brush riding the surface of a commutator. If the surface is smooth, the voltage variations across the brush and commutator are of the order of 2 volts with 110 volts applied. If a complete break occurs, as would happen if the brush were lifted from the surface and let fall on the commutator, then, to make a contact, the voltage variation would be 110 volts.

The tube is supplied with variable grid voltages, varied in steps of 1 volt from zero to 100 volts. The brush drop is connected in series with his voltage and in opposition to it. Now, if the grid voltage is slowly decreased from some high negative value until the tube glows, it is easily possible to determine the brush-voltage drop by noting the voltage at which the tube broke down and by referring to a curve showing the required grid voltage, for the particular plate voltage used, to make the tube conduct.

Harrison states that this device will measure roughness of the order of 0.0001 in. when the commutator is rotating at a peripheral speed of 5,000 to 10,000 ft. per minute and at a temperature of about 100°C.

A Frequency Meter.—A high-speed, direct-reading frequency meter using grid-controlled rectifiers has been developed by Hunt[1] and is offered for sale by the General Radio Company. The circuit of the meter is given. It consists of a modified two-tube inverter to deliver an invariant current pulse to an indicating instrument each time that the polarity of the input signal varies. The average current in the indicator is strictly

[1] HUNT, F. V., *Rev. Sci. Instruments*, February, 1935.

proportional to the frequency of the input signal below 7,000 cycles and approximately so for higher frequencies.

Rectification in the Grid Circuit.—Many circuits take advantage of the fact that rectification takes place in the grid circuit of an amplifier (high-vacuum tube) and in gaseous triodes when the grid draws current. For example, the tube may secure its grid bias when oscillating or generating by causing the grid to swing positive for some portion of the cycle. The grid collects
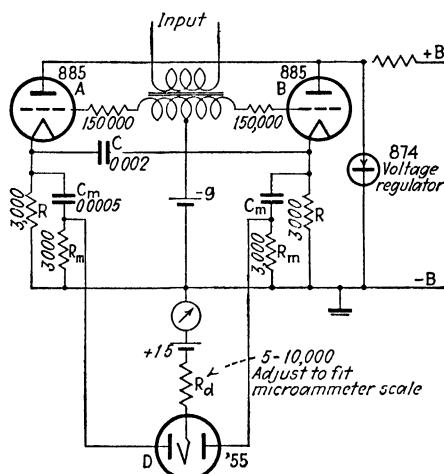
Fig. 40.—Circuit of the Hunt-General Radio frequency meter.

electrons from the cathode-to-anode stream. These electrons constitute a current. This current may be forced to flow through a resistance. The voltage drop along this resistance may be used to bias the grid. All that is necessary is to connect the low-potential end of the circuit attached to the grid-cathode path to the end of the resistor furthest from the cathode. This end of the resistance will be negative, and the grid will then be biased by the voltage drop along the resistance.

Ordinarily, this resistance is by-passed or shunted by a condenser so that a path of low impedance for the a.c. currents in the grid circuit is provided. If, however, the time constant of this RC circuit is high, the grid may "block," or accumulate such a charge of electrons that they cannot leak off through the resistance to the cathode for several cycles of the input voltage. In fact, the RC constant may be so high that the tube will not conduct current at all for periods up to several minutes.

On this principle is laid out most of the time-delay circuits using tubes. Figure 41 shows a simple timer.[1] So long as the switch is closed the condenser stays charged, and the tube conducts. If the switch is opened, the condenser drives the grid negative, then loses its charge at a rate depending upon the value of the resistor and stops conduction for an adjustable period.

This circuit will hold the tube nonconducting for a number of cycles. It is used in resistance welding and in other industrial operations. It is possible to time the conduction of the tube within portions of a given cycle. Thus in Fig.
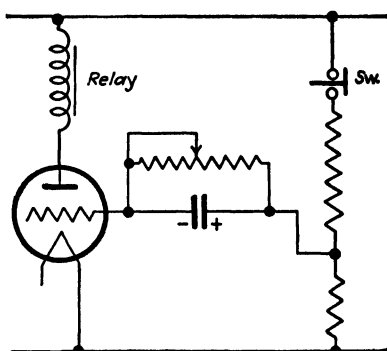
Fig. 41 —Energy storage circuit for timing operations.

42 is an inverter which is self-timing in a manner independent of the anode load. Condenser C_a stops the discharge in one tube when the other conducts and thus produces an alternating flow of current through the output transformer. Grid condensers assume alternate charges like that of C_a but with the difference that
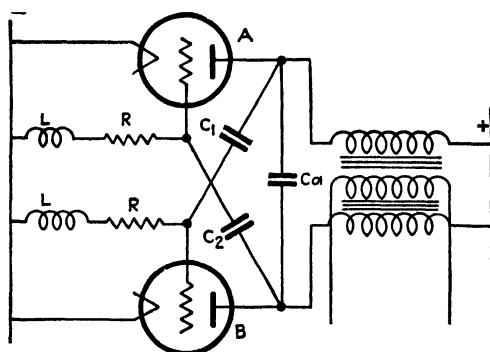
Fig. 42 —Self-timing inverter.

when tube A, for example, is stopped by C_a, the negative charge on the grid side of C_1 cannot leak off, except through R and L and through tube B to the other plate of C_1. This requires a definite time. Inductance in the paths of C_1 and C_2 prevents asymptotic

[1] U.S. Patent 1,552,321.

approach of the condenser to zero voltage and insures positive timing.

A modification of this circuit, useful for regulation of average current flow in a d.c. circuit, for example the d.c. field current is
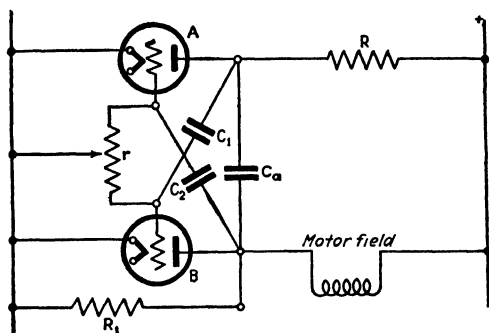
FIG. 43.—Circuit for regulation of field current.

shown in Fig. 43. The tubes conduct alternately, the time tube *B* conducts being controlled by the position of the potentiometer slider. Tube *B* thus acts like a vibrating contact across R_1. Thus this circuit will make possible the control of field current when only direct current is available. Previous methods have required the use of rectified alternating current.

Another condenser discharge method of control is shown in Fig. 44. During each negative half-cycle the condenser is
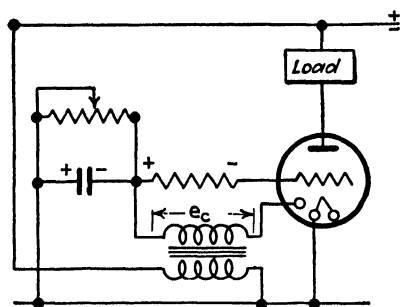
FIG. 44.—Control circuit using condenser in grid lead.

charged negative on the grid side by the voltage e_c taking advantage of the rectifying action of an auxiliary electrode within the tube. Discharge then takes place through a resistance. The point of starting the arc may be controlled by adjusting the

capacity, the resistance, the amplitude or phase of e_c.   Inductance in series with the resistance causes the discharge curve to intersect the curve of critical grid potential at a favorable angle to maintain stable operation regardless of shift in tube characteristics.

Another use of the condenser-resistance circuit is shown in Fig. 45 where a reactor, in theater illumination, etc., is controlled by its individual potentiometer, or by a master potentiometer. Rectifier tube A with C and R provides a basic wave which is
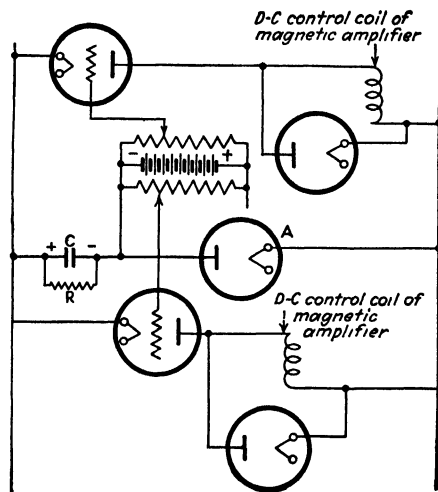
FIG. 45.—Control of current through reactor for illumination, etc.

part of the voltage applied to all grids of all reactor control tubes. Superimposed on this wave in the grid circuit of each tube is the d.c. voltage derived from its individual potentiometer giving control, the magnitude of which depends upon the setting of the potentiometer bias.

A method of control depending upon frequency is indicated in Fig. 46.   An a.c. voltage e_1 is used to charge condenser C through rectifier tube 2 during negative half-cycles of the tube anode voltage e_a.   Although condenser voltage e_c substantially equals e_1 while the latter is increasing (neglecting the small drop in tube 2) e_1 can *decrease* more rapidly than e_c due to the rectifying action of tube 2.   Therefore, e_c decreases in accordance with the natural frequency of C through L and R.   At a lower frequency the period is not sufficient to permit tube 1 to conduct but is sufficient at a higher frequency.   This arrangement is used success-

fully in speed control of slip-ring induction motors, the lines L_1 and L_2 being connected to the slip rings.

High-speed Photography by Means of Gas Tube.—Photographs[1] made at rates of several thousand per second have been

Fig. 46.—Control circuit dependent on frequency

accomplished by means of a grid-controlled rectifier and a mercury lamp by the circuit shown in Fig. 47. The operation of the circuit is as follows: When the switch S is closed, the grid of the

Fig. 47.—Gas-tube circuit for high-intensity light for high-speed photography. (*Edgerton.*)

tube is made positive with respect to cathode. The tube then becomes conducting and allows the energy in the small condenser C_3 to discharge into the primary of a step-up transformer. The resulting high voltage in the secondary is applied to an external

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[1] EDGERTON, H. E., *Electronics*, July, 1932. See also EDGERTON and K. J. GERMESHAUSEN, *Rev. Sci. Instruments*, October, 1932; *Electronics*, August, 1934, p. 250, and March, 1935, p. 94.

connection on the light-pulse tube, and it causes the formation of a cathode spot or electron source. The condenser C_1 now discharges through the tube and because of the volt-ampere characteristic of the mercury lamp the discharge time is short and the current surge high, resulting in a quick intense pulse of light.

By making the tube fire in synchronism with some moving system, a stroboscopic effect is secured. This use of the gaseous triode in sending into a gaseous illuminating tube, of high
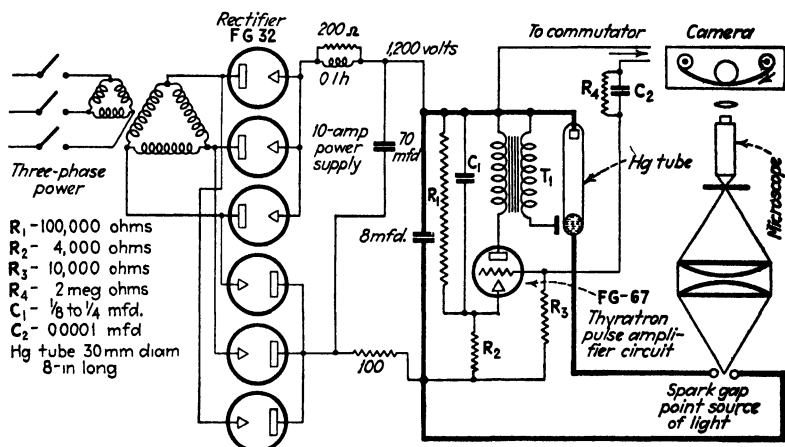
Fig. 48.—Edgerton high-speed microscope camera.

photographic effect if desired, a high sudden current is proving most important in investigating stroboscopically automobile motors, newspaper presses, looms in textile mills, etc. Edgerton has applied his technique to microscopic photography.

The microscope that views the motions to be recorded is fitted with a motion-picture camera the film of which moves continually at a speed of about 200 in. per second, thus permitting 200 pictures to be taken in that time. The light source underneath the specimen is an open spark gap. The intense light from the spark is used to illuminate the specimen to be examined. The light is turned on and off rapidly so that blurring of the picture does not occur.

The voltage applied to the spark gap is controlled by the circuit shown. A three-phase rectifier using mercury tubes provides a 10-amp. rectified-current supply which charges a 70-microfarad

condenser through the resistance shown. This condenser is charged to 1,200 volts and discharges through a 100-ohm resistance into an 8-μf condenser, which is the source of the current through the spark gap. In series with the spark gap and the 8-μf condenser is a mercury tube, containing a mercury pool and an anode. A grid-controlled rectifier, operated in an impulse amplifier circuit, discharges this mercury tube at the required rate. The excitation of the controlled rectifier amplifier is provided by a commutator mounted on the motion-picture camera, so that the commutator trips the rectifier circuit once for every picture to be taken. In this way the spark that jumps the gap is accurately controlled both in its frequency and in its time duration. High-speed pictures of great sharpness and clarity can be taken with such apparatus, and the intense light of the spark is sufficient to make high magnification possible without a dimly illuminated picture. The apparatus does not differ largely from the regulation Edgerton stroboscope now in wide use for high-speed photography work, except that the light source in this case is a spark gap, rather than the more common mercury-discharge tube. The use of the spark gap provides a very compact light source of great intensity, which is ideally suited to the requirements of microscope illumination.

Stroboscopes.—The Stroboglow[1] (Westinghouse) uses a special heavy-duty, "sign-type," cold-cathode lamp. The circuit in Fig. 49 has three units, the power unit, the lamp, and the contactor, all of which fit into a single carrying case. The power unit is essentially a transformer for supplying the necessary voltages to the lamp circuit. The separable lamp unit houses the stroboscopic lamp and all the controls for the electronic timer, which produces the flashes of the lamp at the desired rate. The contactor is an auxiliary piece of apparatus and is used only when it is desired to have the machine being viewed control the flashes of the lamp.

The electronic timer consists of an amplifier tube whose grid circuits are controlled by potentiometers and a range knob. This tube periodically charges a condenser, which, when it reaches the proper potential, causes the grid of a gas-filled timing tube to permit a discharge to pass through its plate circuit. This circuit includes the primary of a special spark coil.

[1] HITCHCOCK, R. C., *Elec. J.*, December, 1935.

The stroboscopic lamp is continuously supplied with direct current which is sufficient to cause a flash only when the spark coil is energized.

The reflector optical system directs the light over a wide area when used a few feet away, eliminating special precautions necessary to make focused light fall on the desired spot.
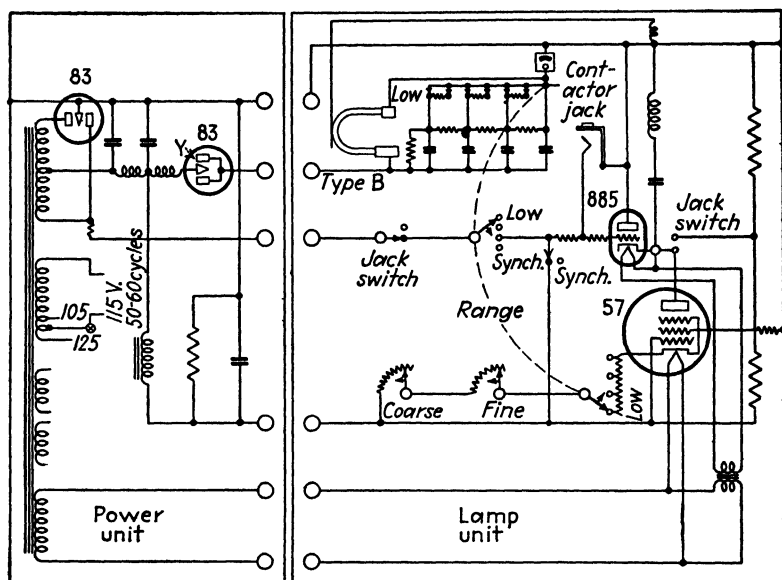
FIG. 49.—Stroboglow circuit.

An added feature is a switch by means of which the power-line frequency 3,600 per minute on a 60-cycle line, will permit flashes to measure slip or lag of synchronous machines.

The schematic circuit in Fig. 50 is taken from "Electron Tube Experiments," a series of laboratory experiments to demonstrate the characteristics and applications of various tubes. In the stroboscope, rotating or vibrating machinery is illuminated by intermittent beams of light which are turned on and off in synchronism with the movement of the body under inspection. If, for example, the light is turned on briefly at a given point in the cycle, the object will seem to stand still because only this point in the cycle will be visible.

Thus by the stroboscope (Westinghouse term is Stroboglow), various moving bodies such as disks on motors, motor-driven

wheels, armatures, or rotors may be made to appear to be stationary to the eye, even though running or rotating at full speed. If a cardboard disk about 12 in. in diameter is placed on the shaft of the synchronous motor, and various letters and figures pasted or painted on the disk, they may be made to appear stationary, although the disk is rotating at synchronous speed. This has been called "motionless motion."
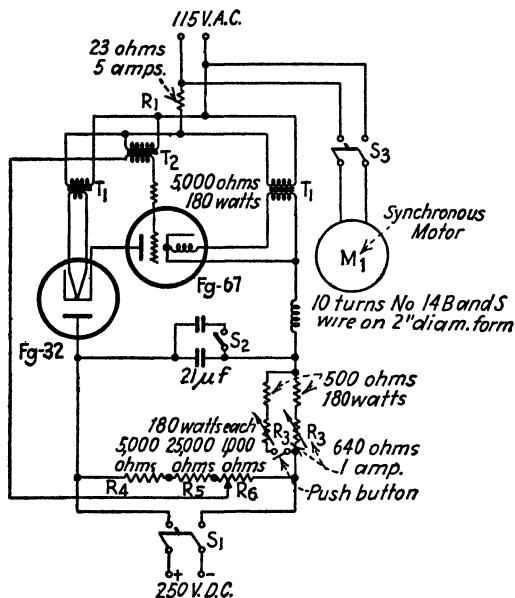
Fig. 50.—Tube-controlled stroboscope circuit.

Two tubes, a two-element rectifier and a controlled rectifier, are used in series in this equipment, so that a maximum amount of "stroboscopic light" may be obtained. However, the life of the tubes is rather shortened by the large peak currents which are inherent with this type of circuit.

For the cathodes to reach their correct operating temperatures, they should be excited approximately 5 min. before the d.c. line switch is closed.

Two light frequencies may be had by the use of this circuit. When the switch S_2 is closed, the frequency of the light source will be exactly half that when the switch is in the open position.

Practical Controlled Rectifiers.—The ability of the grid in gaseous triodes and tetrodes to control the value of the average current flowing into a load circuit lends itself to the production of direct current from alternating current at good regulation and at a high degree of constancy as to voltage. Numerous applications of this general type have been made, several of them to laboratory usage where a high degree of control is necessary or desirable. A high-precision source of direct current at voltages from 50 to 5,000 has been described by C. B. Foos.[1] With this circuit, as shown in Fig. 51, it is possible to hold the voltage at any point within 1 per cent independent of supply-voltage fluctuations up to 15 per cent and variations in load current up to 2 amp.
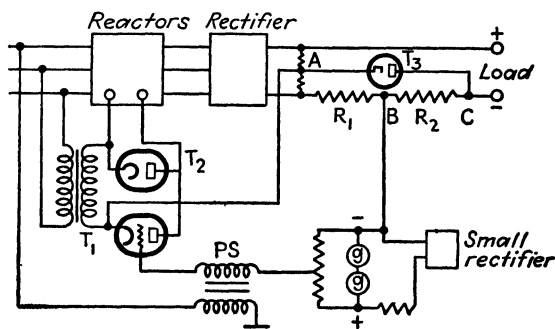
Fig. 51.—Vacuum-tube-controlled rectifier.

Furthermore, the current output can be limited to any value from 1 amp. up even on short circuit without affecting the voltage regulation up to the current limit.

The main unit is a 10-kw., full-wave, hot-cathode rectifier, rated 220-volt, three-phase input, 6,000 volts d.c. output. In the a.c. input to the set are three reactors with d.c. saturating windings. By means of these saturating windings, the impedance of the reactors may be varied, from a very high value (when no direct current flows in the saturating windings) to a low value (when full saturating direct current flows in the windings). Thus, the current supplied to the saturating reactor determines the voltage on the rectifier primary and hence the output voltage of the rectifier.

The amount of this saturating current is controlled by a three-element mercury-vapor control tube T_1, and so the focal point of the whole con-

[1] Foos, C. B., *Elec. Eng.*, April, 1934, p. 568. See also KIMB, R., A Thyratron Laboratory Rectifier, *Electronics*, August, 1933, p. 219.

trol is the voltage applied between grid and cathode of this tube, which determines the amount of current that it will pass; how will be seen later. In this grid circuit are connected a phase-shift voltage PS, a standard voltage g-g, and a control, or comparison, voltage. As may be seen, the control voltage is taken from the potentiometer, at points A and B. It is so connected that its polarity tends to act on the set to reduce the output voltage. In series with it, and opposing its effect, is the standard voltage; the difference between the two controls the set. This standard voltage is taken from a potentiometer across two glow tubes g-g connected in series. Each of these tubes maintains a constant voltage drop of about 90 volts over a considerable current range. They are supplied with a much higher d.c. voltage from a small rectifier through a high resistance, so that they will maintain 180 volts on the potentiometer over a large range of supply voltage. As the voltage regulation is obtained by the difference between the standard and control voltages only, it may be seen that the set will hold constant d.c. output voltage regardless of line-voltage fluctuations.

Resistor R_1 is the compound resistor. The voltage drop across it, owing to the load current, acts against the control voltage, tending to raise the output voltage.

Resistor R_2 is the current-limiting control resistor. Point C is connected to point A through the rectifier tube T_3. At no load, point A is the more positive, and current cannot flow through the rectifier from A to C. As the load current increases, the voltage drop across R_2 rises until point C becomes more positive than point A; current then flows through the rectifier from C to A, tending to raise the potential of point A and hence the control voltage, which acts to reduce the output voltage; thus the control is shifted from the voltage to the current at this point. Both R_1 and R_2 are variable, because the current limit is adjustable, and at the current limit, IR drop in R_1 is approximately equal to the standard voltage. R_2 compensates for the drop in R_1.

The circuit shown in Fig. 52 (General Electric book of tube experiments) furnishes a full-wave rectified and filtered current, the magnitude of which can be controlled by means of the variable resistor. The resistor and capacitor, which are connected in series across the a.c. supply voltage, form a phase-shifting network to supply the grids of the tubes through a transformer T_2. This voltage is in phase with the supply voltage if the resistance is zero and lags the supply voltage as the resistance is increased, up to a theoretical value of 180 deg. However, this range is not entirely available, since for the high values of resistance the grid transformer current causes excessive regulation in the phase-

shifting network. It is suggested that a 5-amp. d.c. meter be placed in series with the output load and a 250-volt d.c. meter be placed across the output load. The variable resistor should then be set at various definite points, and the output voltage and current noted for each setting. The phase shifting may be studied by placing one element of an oscillograph across the secondary of the grid transformer T_2 and the other element across the secondary of the plate transformer T_1; or, if desired,
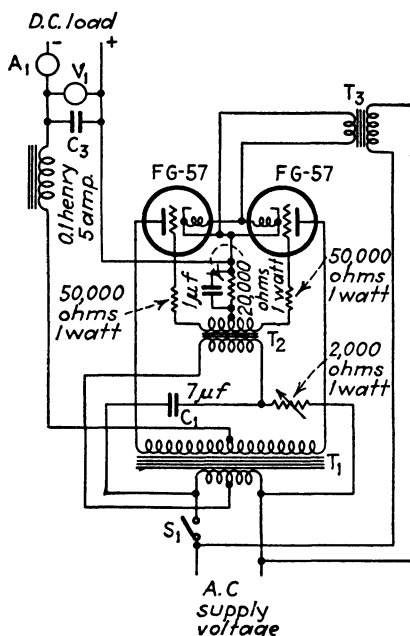
Fig. 52.—Grid-controlled rectifier circuit.

the current element may be placed in series with the load, and the voltage element placed across the plate and cathode of one of the thyratron tubes and the effect studied.[1]

Tube Control of Wire Drawing.—An example of the control of electric equipment during operation by means of grid-controlled rectifiers is found in the wire-drawing shops of the General Electric Company at Schenectady. Very fine wire is reeled under a strain that is a large percentage of the ultimate strength

[1] For the use of thyratron rectifiers supplying power to sodium-vapor lamps, see WESTENDORP, W. F., *Gen. Elec. Rev.*, August, 1934, p. 368.

of the wire, say 5 oz. out of 7. The wire must be kept at the proper tension while it is being reeled and this tension is maintained by the use of electron-tube equipment as described below.

The wire passes from a large reel through the wire-drawing equipment where it is drawn down to the desired size, and thence to a small spool where it is rereeled. As the wire is drawn at a constant rate, the speed of the rereel spool must be constantly decreased to compensate for the increasing diameter of the surface on which the layers of wire are being wound.

The rereel spool is driven by a small d.c. motor, the armature of which is supplied with power by the rectifying action of gaseous triodes. A small reactor is included in the grid circuit of these tubes. The reactance of this solenoid determines the phase relationship between grid and plate of each tube and thereby governs the average current taken by the motor through the tubes.

To correlate the tension of the wire and the reactance of the coil, the wire passes under a pulley that is held down by an adjustable spring so that the pulley goes up when the tension increases. To the pulley is attached the core of the reactor, the coil of which is in one side of the grid-control bridge. The loop on which the rider pulley rides decreases when the rereel motor runs too fast drawing the core into the reactor, increasing its reactance, varying the phase of the grid so that the tubes pass less current, and slowing down the motor. Hence the motor torque varies instantly with the wire tension. Copper wire three mils in diameter is reeled at 4,000 ft. per minute. So far as the reeling device is concerned, a speed of 80,000 ft. per minute could be attained.

Conveyor Synchronization.—A similar application has been made in the processing of rubber by the B. F. Goodrich Company. In a number of the operations, conveyors are used and it is important that the speeds of the various conveyors in a chain be synchronized. On a loop of the material between conveyors (Fig. 53), ride wheels similar to the rider pulley in the wire-reeling operation. Solenoids actuated by these wheels govern the current rectified by the thyratrons and thus synchronize the speeds of the motors driving the conveyors.

Another application of the solenoid-grid-control bridge circuit is found in plants where two conveyors are feeding dissimilar

materials to a hopper and it is necessary to maintain the proportions within close limits. The conveyor carrying the varying amount of material passes over a balanced weighing roller. When the roller is depressed by excess weight, it lowers a solenoid into the reactor coil and causes the tubes to speed up the motor on the other conveyor, thus maintaining the proper proportions.

Electron-tube Impact Meter.—By making use of the difference in inertia of two masses and a grid-controlled rectifier, Westinghouse engineers have constructed an impact meter. The measuring part of the instrument consists of a small cylinder, 2 in. in
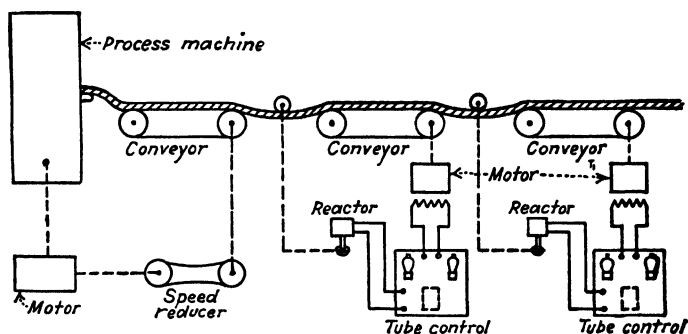
FIG. 53.—Synchronization of conveyor belts by controlled rectifiers.

diameter and 4 in. high and having two terminals, one at the top and one on the side. The cylinder contains a body of relatively high inertia, which is partly supported by a helical spring and partly by the electrical contacts. These contacts are located below the body and are normally closed. The contacts are connected to the two terminals mentioned above.

This unit is placed on the object upon which the impact is to be measured. Under the force of the impact the cylinder tends to drop away from the body of higher inertia, so that the contacts between the two are momentarily drawn apart. The impact necessary to cause the contacts to open may be varied by changing either the mass of the inner body or the size of the spring.

Each of six of these mechanical units is connected to a phone jack which is plugged into one of the six receptacles in the meter. Six tubes are used, one for each unit. For each of the six circuits, a potentiometer composed of small fixed resistors is connected across the power supply. These resistors are adjusted to keep the grid, which is connected to an intermediate point, at a

potential too low for breakdown.   However, when the external unit is subjected to an impact of sufficient intensity, its contacts open, thus opening the negative end of the potentiometer and throwing the grid to a more positive potential causing momentary breakdown of the tube.   The fixed condenser across the potentiometer also discharges, so when the contacts are again closed the voltage across the tube is very small, thus stopping the discharge. This cycle of operation is repeated for each of the impacts which opens the contacts, and by noting the tube or tubes flashing, the value of impact is determined.

Electron-tube Micrometer.—When necessary to indicate or measure small dimensions of a few thousandths of an inch, the use of a controlled rectifier tube in connection with a micrometer has given good results.   For example, when measuring the diameter of very small wire, or the dimensions of very ductile or plastic materials such as soft copper, rubber, or ceramic materials the work may be deformed between the anvils of a hand micrometer.   The operator's sense of touch may not be sufficiently sensitive for exact readings of the micrometer because the material being measured must build up resistance to the micrometer screws, and the compression of the micrometer jaws may alter the dimension being measured.   With the tube micrometer no contact pressure is required, and the tube is far more sensitive than any operator's sense of touch.

In operation the micrometer points are connected to the grid and plate of the controlled rectifier.   When contact is made, the tube passes current and indicates such to the operator either by some relay device or by the change in the color of the tube itself.

In an investigation[1] of the elastic hysteresis or retarded elastic deformation of material used for spiral instrument springs, the tube micrometer proved itself of great value.   More recent work used a standard light relay (amplifier) with the phototube replaced by the micrometer contacts.

In measuring the creep characteristics of suitable spring alloys, the most difficult problem is to obtain sufficient sensitivity.   This requires a measuring device that will detect changes in spring deflection as small as 0.01 per cent of the full-load deflection and do it without altering the deflection.   Various methods have been

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[1] CARSON, R. W., *Elec. J.*, February, 1936, p. 106; *Electronics*, June, 1932; *Elec. Eng.*, February, 1934.

employed including both optical and mechanical means.   Optical
devices, however, lack sufficient sensitivity, and mechanical
means all introduce some load on the spring being tested.

Carson's device uses electronic means'of indicating point of
contact between a hand micrometer and a test specimen in the
form of a small cantilever beam.

The hand micrometer, fitted with a needle point, is screwed
down until the point just touches the specimen.   The contact is in
series with a resistance of 30 megohms and is wired to the light
relay with this contact circuit replacing the photo-electric tube.
The instant of contact is indicated on a voltmeter connected
in parallel with the contactor coil on the relay.
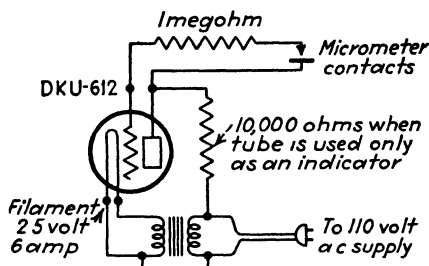
FIG. 54.—Glow-tube micrometer.   The tube glows when contact is made.

Because of the high sensitivity of the relay, an indication is
obtained before physical contact actually takes place.   Continued
operation leaves no imprint on the specimen, and the needle point
remains sharp even when magnified to 150 diameters.   In fact,
the device "feels without touching."

The micrometer is read on a drum having 20 divisions for
each mil.   By means of a magnifier, readings can be estimated
readily to the nearest one-fifth division, making it possible to
take readings to the nearest 0.00001 in.   However, the indicating
system is sensitive to changes that are smaller than can be read.
By means of the recording device which is used on the microm-
eter, movement of the micrometer barrel is mechanically mag-
nified so that changes as small as 0.000002 in. can be read.   This
distance is about one-tenth of the wave length of green light
and therefore is equivalent to one-tenth of a fringe in an
interferometer.

With this high sensitivity, creep at normal temperatures can
be determined quickly and easily.   In a typical test, the results

of which are shown in the diagram, the creep during the first 20 min. after applying the load was 0.0097 in. After heat treatment the creep under identical load conditions was only 0.0013 in. Instead of requiring days of time, only a few minutes of testing gives an accurate determination of creep and makes it possible to find quickly the best material and heat treatment.

Floating Grid Circuit.—The circuit in Fig. 54*A* is a sensitive device for micrometer work or for detecting contacts or changes in electrical or mechanical quantities. The grid piles up a charge of electrons which cannot leak off to the cathode provided the condenser is of good quality. If, however, the grid terminal is touched or closely approached, electrons leave the grid, permitting its negative potential to decrease, with the result that plate current flows, and the relay operates. A phototube can be connected across the condenser so that the circuit operates as a standard light relay.
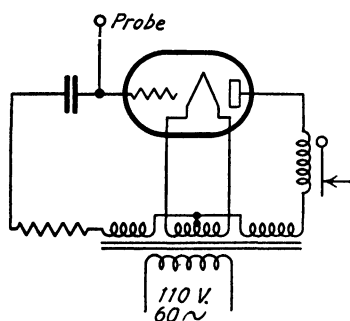
Fig. 54*A*.—Floating grid circuit. When the probe is approached, the relay closes.

If a metal probe is connected to the grid terminal, inspection of objects for size can be carried out very effectively by this circuit. The fixture holding the object to be inspected is grounded, and the grid terminal connected to the probe is brought to contact the work piece when the tube conducts. If the piece is undersize, the tube does not conduct; if it is correct, the tube conducts; and by the use of more than one probe, pieces may be sorted to within 0.00005 in. for under-, correct, and oversize.

Power Applications.—Vacuum tubes when contained in a suitable circuit and properly controlled offer a means to transform electric power from one form to another. For example, alternating current can be changed to direct current or vice versa; direct current of one voltage can be transformed to direct current of another; alternating current can be changed in phases and frequency; and power factor can be corrected. The same tube offers a solution for the troubles of overcommutation, speed limitation and control, arcing, and wear, since it is quite capable of replacing the well-known commutator in d.c. motors.

All of these things have been proved in the laboratory and test. At this writing, all of the foregoing applications of vacuum tubes, with the exception of the d.c. transformer and the static condenser, are in practical operation under service conditions.

The Inverter.—One of the greatest potential fields for the grid-controlled rectifier is in the field of inversion, the production of alternating current from direct current at high voltages; and the change from one voltage or frequency to another. The simplest form of inverter consists in feeding direct current to a controlled rectifier; then by some means of commutation the grid voltage of this tube is so varied that occurring in the plate or anode circuit are pulsations or alternations of alternating current.

The grid-controlled rectifier as an inverter is a new tool of vast possibilities, particularly now that tubes of very high power are available.

Inversion—Production of Alternating Current from Direct Current.—When a three-element gas tube is used for the function of inversion, the tube acts essentially as a switch to change the unidirectional flow of current from the d.c. source to alternate sections of transformer windings. Of course, the production of alternating current from direct current is not confined to grid-controlled rectifiers, nor is it a new electron-tube phenomenon. Any oscillator of the high-vacuum type will produce alternating current of almost unlimited range of frequency and considerable range of power from a bank of batteries. Here, however, the process is very different. Furthermore the production of a.c. power from a bank of batteries by this means is expensive, the high-vacuum tubes suffering in comparison to three-element gas tubes because of the high internal voltage drop which reduces the over-all conversion efficiency and very distinctly limits the power obtainable in this manner.

Gaseous-tube inverters will change large amounts of d.c. power to a.c. and do it at high efficiency.

All inverters, of both the high-vacuum or oscillator type and those using the newer tubes, the three-element gaseous tube, must have some form of energy storage or flywheel. In the power circuits using grid-controlled rectifiers this energy storage is required to commutate the current flow from one winding to another and to take control of the circuit long enough to aid in the

de-ionization of the gas within the tube and so to reestablish grid control.

Although most inverter circuits involve two tubes, there are several single-tube circuits for performing the function of getting alternating current from a d.c. source.[1] Consider Fig. 55a. Assume the switch to be closed on a d.c. source at a time when the condenser is discharged. Since no voltage exists across the condenser, the cathode of the tube is at the same voltage as *b*, the negative side of the line. The grid is positive because of its
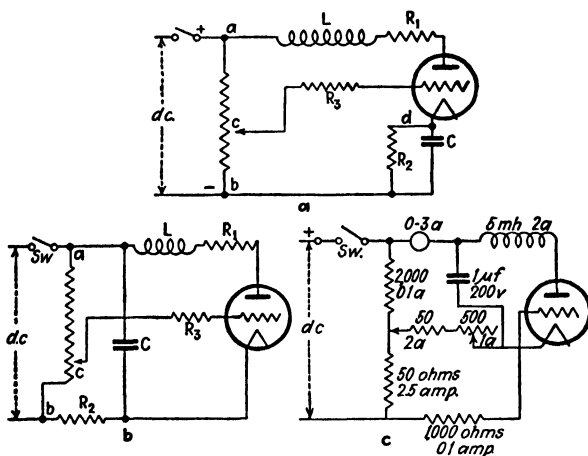
FIG. 55.—Fundamental single-tube inverters.

position on the voltage divider, *a-b*. If this positive voltage is of the proper magnitude, the tube starts to conduct.

The current passes through the inductance L, the resistance R_1, the tube, and the condenser C shunted by the resistance R_2 and back to the line. If R_2 across the condenser is high enough, and R_1 is low enough, the condenser will quickly charge, and the voltage across it will soon equal the line voltage. Ordinarily, the current flow would cease at this instant, but because of the inductance, current will continue to flow because of the collapsing flux about the coil which induces an e.m.f., forcing current to flow through the condenser.

As a consequence of this continued flow, due to the inductance, when the current finally ceases, the condenser is charged higher than line voltage and the anode is now more negative than the

[1] See LORD and LIVINGSTON, *Electronics*, April, 1933.

cathode by this voltage. Therefore, until this charge leaks off through R_2, the tube will not conduct current again. When, however, the voltage across the condenser has decreased to the point where the difference in potential between grid and cathode is equal to the critical voltage, the cycle will be repeated.

The overcharging of the condenser enables the grid to retain control of the discharge for a period long enough for de-ionization to take place. Thus the tube commutates the flow of current.

The second fundamental single-tube inverter is shown in Fig. 55b. In this case when the switch is closed the cathode and anode are at almost the same potential (the condenser is uncharged), and the grid is at a negative voltage by the amount of the drop along a-c. While the condenser is charging through R_2 the tube does not conduct. Charging the condenser lowers the voltage of the cathode, and when it reaches the value which will give the grid-cathode potential the critical value, the tube will conduct. At this point the condenser discharges through the inductance and R_1. The voltage across the condenser is now reversed, because of the overcharging effect, making the anode negative long enough for de-ionization to occur and give control to the grid again. Now the condenser charges again and the cycle is repeated.

Occasionally the circuit is used without the potentiometer, the grid being connected to the negative side of the line. The lack of the potentiometer removes the ability to control the frequency with which the condenser and tube discharge and it tends to make the timing more susceptible to error.

In Fig. 55c are typical constants of a single-tube inverter circuit described by E. D. McArthur, *Gen. Elec. Rev.*, November, 1933.

Single-tube Inverter Applications.—After setting R_2 and the potentiometer C to produce the proper frequency, a small synchronizing voltage introduced in series with the grid circuit will maintain the proper frequency of inversion so that the tube may be run in synchronism with some other circuit. Multiple or submultiple frequencies may be synchronized in this manner.

In practice the inductance and R_1 would probably be a transformer, from the secondary of which would be taken the desired alternating current. The leakage inductance is usually sufficient to overcharge the condenser. If the voltage ratio of the trans-

former is of the correct order, the circuit may be used to light neon signs, the circuit then becoming an interrupter induction coil.

If R_2 is replaced with an emission-limited vacuum tube to maintain a constant charging or discharging current through the condenser and the time of conduction is made very small, a saw-tooth wave form will be secured, useful in cathode-ray tube work, for television, or for other purposes where a sharp break is desired. In welding control by grid-controlled rectifiers this method of timing is used.

A d.c. potential may be used in series with the saw-tooth wave which, varied in amplitude according to some desired time function, will control the proportion of the time the resultant voltage is positive. This voltage applied to the grids of other tubes will control the ratio of the time that current is passed to the time it is off. The number of welding spots per second may be varied by changing the frequency generated by the inverter.

Another use of the inverter is for stroboscopic work. For example, a synchronous motor rotor and shaft will seem to stand still if the inverter is synchronized from the source used to run the motor or the rotor of an induction motor seems to move backward proportional to slip frequency. If a shaft to be observed is not running in synchronism with any a.c. source, a small synchronizing voltage may be introduced into the grid circuit by the use of small contacts or by inducing a voltage in a small pick-up coil once a revolution.

Inverter Frequency Meter.—With a slight modification a calibrated variable frequency stroboscope can be produced, useful as a tachometer in observing the period of repeating phenomena without affecting the phenomena. If the alternating voltage is held constant in either of the fundamental circuits shown in Fig. 55 and the value of R_2 varied, the reading of a d.c. ammeter in series with the tube anode will be directly proportional to the frequency. If the frequency of the stroboscope is varied until the highest frequency which gives a single image of the moving part is obtained, a reading of the meter will give the correct frequency. To check this reading, doubling the stroboscope frequency should produce two images 180 deg. out of phase.

If this circuit is further modified for external excitation, (shown in Fig. 56), the reading of the d.c. ammeter is propor-

tional to the frequency of the excitation. This makes it applicable to a number of frequency- or speed-measuring problems. The addition of the tube T_2 insures the condensers always charging to the same value at high speeds and a glow tube T_3 affords freedom from line-voltage-variation errors.

Relaxation Inverters.—Single-tube inverters somewhat different from those described above have been worked out by H. J. Reich[1] and Dr. Palmer H. Craig.[2] The latter uses a Tungar rectifier.
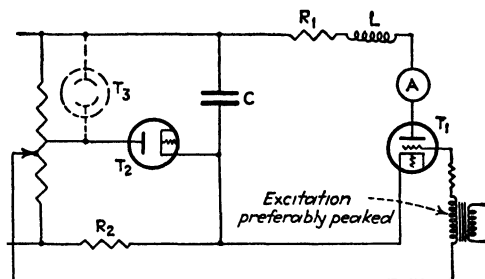
FIG. 56.—Addition of rectifier T_2 and glow tube T_3 to free a frequency meter from errors due to line-voltage variations.

In the Reich circuits the tubes with low de-ionization time are preferable, as in all inversion circuits, but most mercury-vapor tubes will oscillate when the current is limited by the load resistance to a sufficiently low value. The basic circuit consists merely in an output transformer in the anode circuit and in series with the d.c. supply. Across the plate-cathode path are an inductance and capacity. The grid is driven from an a.c. source of the required frequency and amplitude to produce alternations of plate current which appear across the primary of the output transformer. The source may be any oscillator, a source of commercial power and frequency, or in the self-excited circuits may be fed back from the output.

The frequency of the output voltage need not be the same as that of the input grid voltage. In fact, several oscillations may take place before a single cycle occurs in the output. At the end of a series of oscillations the grid may have become sufficiently negative to prevent another breakdown. Circuit

[1] REICH, H. J., *Rev. Sci. Instruments*, October, 1932; March, 1933; *Elec. Eng*, December, 1933.

[2] CRAIG, P. H., *Electronics*, May, 1933, p. 639.

constants and the d.c. and a.c. voltages used control the ratio between the time current flows in the output to the time it does not. It is possible to arrange the circuit so that a single oscillation takes place per cycle of output.

A self-excited circuit which oscillates only once per cycle is shown in Fig. 57. The coil L_2 coupled to L_1 has a large number of turns. The process of inversion is as follows: Condenser C_1 discharges through L_1 and induces a voltage thereby in L_2. This voltage charges, through the tube, condenser C_2. When C_1 is discharged the tube de-ionizes but because of the rectifying action of the grid circuit, the charge on C_2 cannot leak off through the tube. The grid and condenser are, therefore, negatively charged and the tube cannot pass current even after the anode rises to a positive value. The grid charge, however, finally leaks off through R_g and the cycle is repeated.

Fig. 57.—Self-excited oscillator of the relaxation (condenser-resistance) type.

The frequency of oscillation is controlled by the capacities C_2, R_g, by the turn ratio between L_1 and L_2 and the coupling between them, and by the setting of the potentiometer P.

An auxiliary rectifier may be used instead of depending upon rectification in the grid circuit. The rectifier (Fig. 58) must supply about 25 ma. and be capable of withstanding an inverse voltage of 200 to 300 volts. According to Reich, some work has been done with additional electrodes within, or even outside, the envelope. It may be simply a wire sticking out of the press through which the normal tube electrodes project.
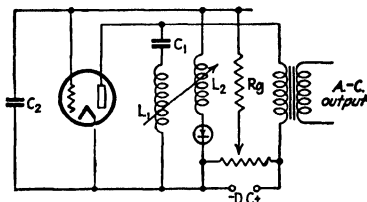
Fig. 58.—Addition of rectifier to Reich oscillator (Fig. 57) to eliminate dependence upon grid rectification.

An external grid may even take the place of that normally placed within the tube so that a two-element rectifier may be made to invert by controlling the discharge through a screen of wires put about the outside of the envelope. Furthermore, Reich has shown that putting the tube in an electromagnetic

field accomplishes the control function much as the external electrostatic grid controls the tube.

Reich[1] states that using the FG-67 at frequencies of 60 to 120 cycles, an output of up to 100 watts may be obtained at anode efficiencies of the order of 70 per cent when operating from 120 volts direct current. With the FG-37 similar performance is obtained with the additional advantage that the filament may be heated directly from the 120-volt supply. The FG-67 requires 5 volts for the filament and this may be obtained from direct current through a resistor. After the production of alternating current is begun the filament may be lighted from alternating current.

Reich[1] states that with a tube of the FG-67 type on a 115-volt d.c. supply, the relaxation inverter will deliver 80 watts with

Fig. 59.—Direct-current transformer using gaseous triode.

an anode efficiency of 50 per cent at 60 cycles. At 75 cycles it will supply 80 watts at 70 per cent efficiency or 100 watts at 50 per cent efficiency. Between 200 and 300 watts at efficiencies ranging up to 75 per cent can be obtained at 60 cycles from a 230-volt supply. Since the power varies as the square of the voltage, considerable power can be developed at high voltages. Because of poor voltage regulation and variation of wave form with load, this type of inverter will probably prove useful in apparatus which require fairly constant a.c. power as in radio receivers or neon signs. In the latter application the poor regulation is an advantage.

The Direct-current Transformer.—Since from direct current the tube will produce alternating current by the process of inversion, it is apparent that a d.c. transformer[1] may be built by the use of a controlled rectifier plus a two-element rectifier. The circuit is shown in Fig. 59 where direct current supplies the controlled rectifier with its power, the tube furnishes alternating current to the second rectifier and the d.c. output at higher voltage is taken off the condenser C_3. With this apparatus Reich obtained 80 to 100 ma. at 400 volts from the 120-volt supply. C_1 had a capacity of from 10 to 15 μf. With the FG-67 a 32-volt source of supply could be used.

[1] REICH, *loc. cit.*

Two-tube Inversion Circuits.[1]—Although the single-tube circuits described above are practical, more complicated arrangements are ordinarily employed. The principles controlling the operation of several of these circuits will be found below.

(a)

(b)
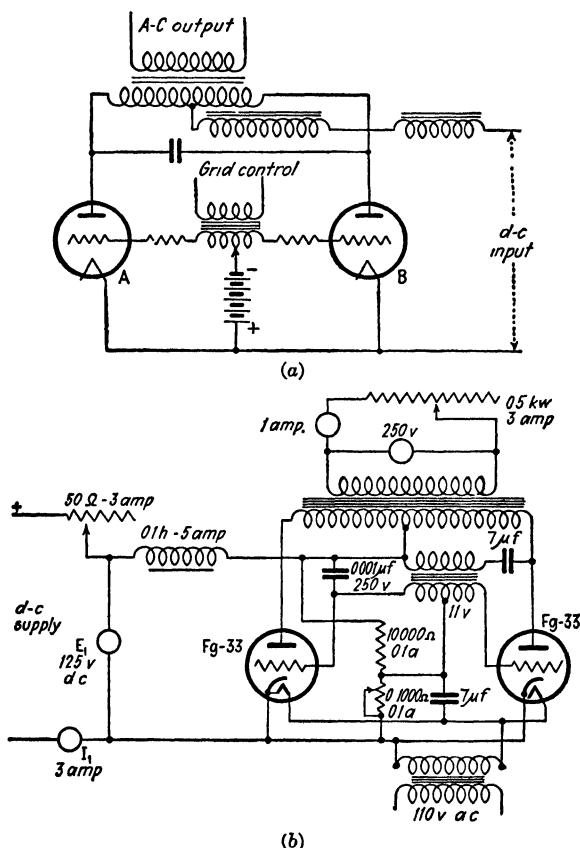
Fig. 60.—Parallel-type inverter with typical circuit constants.

The parallel inverter, shown in Fig. 60, is a device for obtaining a.c. output from a d.c. input, which is definitely related in frequency and phase to the a.c. grid excitation. The grids, normally biased negatively, are excited so that one is positive when the other is negative. During the positive half cycle of grid excitation, tube A will conduct while the anode of the tube B is at line potential. During the negative half cycle tube B will

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[1] THOMPKINS, F. N., The Parallel Type of Inverter, *Elec. Eng.*, April, 1933.

conduct, thus lowering its anode voltage to the tube drop. , Since
the tubes are tied together by the capacitor, the anode voltage
of *A* will go negative because the capacitor cannot discharge
immediately. If the circuit constants are such that the existing
ions can diffuse before the anode voltage becomes positive, the
grid of tube *A* will resume control. Similarly if the grid of tube *B*
is made positive and that of tube *A* negative, the current will
again shift tubes. The circuit is started and stopped by switch-
ing the d.c. source. The wave form of this type of inverter tends
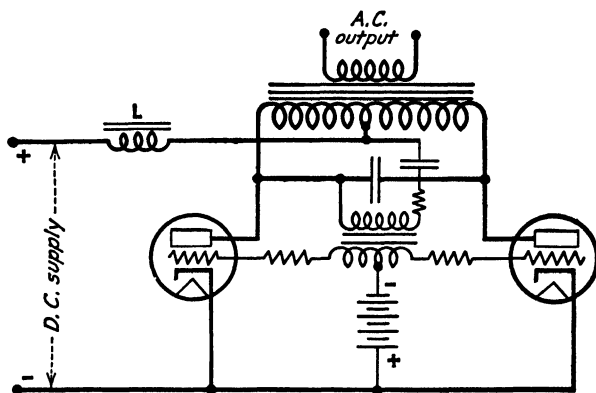
Fıg. 61.—Inverter supplied with excitation by *LC* circuit coupling anode to grid.

to be rectangular but may approximate a sine wave with suitable
circuit constants.

The circuit in Fig. 61 shows the parallel inverter arranged for
self-excitation instead of being driven. The circuit will invert
at the frequency determined by the constants of the grid-circuit
apparatus. The circuit is stopped by switching the d.c. supply.

These circuits may be used to supply a.c. power from a d.c.
source or to supply frequencies higher than 60 cycles as fre-
quently desired for special purposes.

Figure 62 shows a circuit for a separately excited series-type
inverter which may be used as a source of alternating current
from d.c. supply, or as a high-output amplifier to reproduce phase
and frequency. The grids of the tubes are excited so that one is
positive when the other is negative. Bias batteries keep the grids
normally negative. If a d.c. voltage is applied to the plate of
tube *A*, when its grid is positive, current will flow through the
tube, half of the reactor *X*, capacitor *C*, and the primary of the

load transformer *T*. When *C* becomes charged, the current stops. In the next half cycle of excitation the capacitor discharges through the other half of the reactor *X*, tube *B*, and the load transformer *T*, thus furnishing the load with an alternating current.
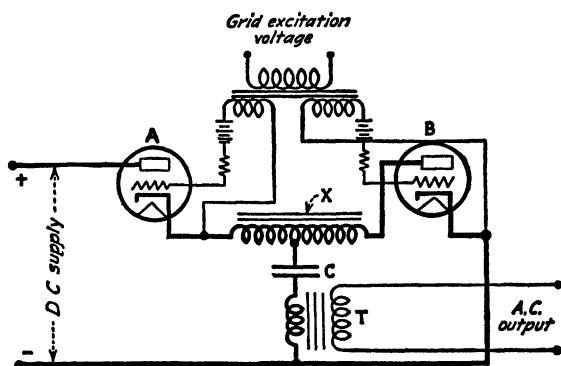
FIG. 62.—Separately excited two-tube inverter.

In Fig. 63 is shown a self-excited inverter circuit having a special control feature. In this circuit the grid excitation is obtained by means of the mutual inductance between the two windings of the grid transformer. This permits the inverter
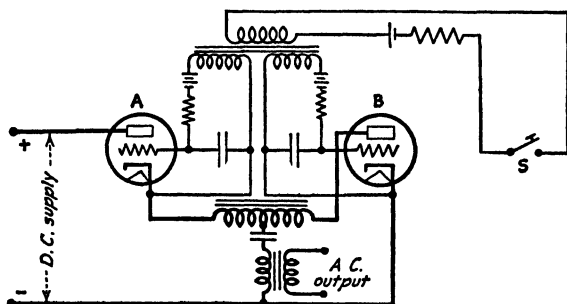
FIG. 63.—Circuit with mutual inductance between grid windings to permit operation into low-resistance load.

to operate into loads of low resistance. The operation of the inverter may be stopped and started by removing or restoring the grid-transformer coupling. This can be done by means of the switch *S*, shown in the diagram, without switching the d.c. supply.

The circuit shown in Fig. 64 is similar to the one in Fig. 63 but is arranged for impulse or push-button control. When the "start" button is pressed the inverter will commence oscillation and the load will be energized. It will continue to operate until
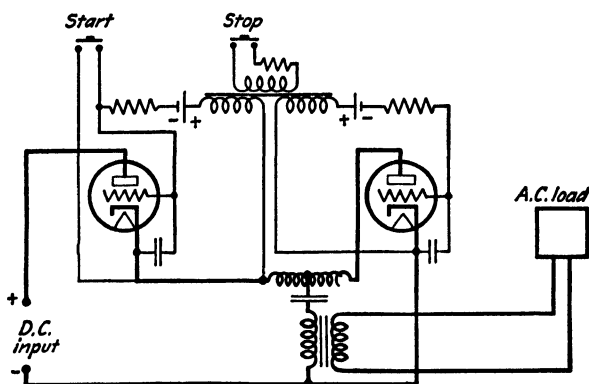
Fig. 64.—Push-button controlled inverter

the "stop" button is pressed, which causes the inverter to stop oscillating, and no further action will occur until the "start" button is again pressed. No switching means in the d.c. power-supply circuit are necessary.
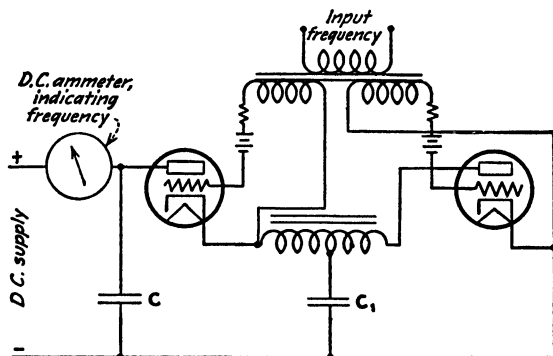
Fig. 65.—Inverter acting as frequency meter. Output is proportional to frequency.

The circuit shown in Fig. 65 employing two tubes may be used as a frequency indicator. It furnishes a direct current which is proportional to the *frequency* of the voltage applied to the grids of the tubes and within limits independent of the grid *voltage*. The device operates on the series-type inverter principle.

Circuit constants of a typical two-tube inverter will be found in Fig. 60b taken from E. D. McArthur, *Gen. Elec. Rev.*, November, 1933.

Practical Inverter.—The circuit in Fig. 66, taken from the General Electric book of experiments already cited, is a practical one.

This type of circuit is used for the timing circuit in the tube control for resistance line welding. It may be used to generate frequencies of below 1 to above 10,000 cycles per second, from direct current. The output obtainable depends upon the rating of the specific tube used.

This type of circuit may be used for stroboscopic purposes and also to study how frequencies may be generated by means of electron devices rather than with mechanical equipment. The wave shape of the output is quite interesting; and when studied with an oscillograph, the vibrator shunt should be connected series with the inductance to note the tube current and in series with R_3 to note the charging current of the condenser.[1] The frequency of the inverter is dependent mainly upon the values of the condenser and R_3. By decreasing the value of the condenser, the frequency of the inverter is increased. This frequency may be varied over a small range by changing the value of R_3.

The grid connection to the potentiometer R_1 should be kept near the negative-potential end in order that the maximum power output of the inverter may be obtained.

Comparison with Rotating Machinery.—Since the reliability and dependability of the inverter will be judged by comparison with rotating-machine type of converters, a comparison may well be drawn at this time. The rotating machine is more certain in its operation because it does not have the variable conditions of changing tube characteristics. This does not mean that the

Fig. 66.—Single-tube inverter, producing audio-frequency currents from direct current.

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[1] On the output wave shape of controlled rectifiers, see STEBBINS, F. O., and C. W. FRICK, *Elec. Eng.*, September, 1934, p. 1259.

inverter is not so satisfactory as the rotating machine, but that greater care is required in the design of the electrical circuits and greater factors of safety employed in order that satisfactory operation may be realized. Experimental tests have shown the tube inverter to be able to start a thousand times under widely varying line and load conditions without a single failure. Failure to operate usually is the result of maladjustment of some portion of the circuit and results in failure of the protective fuse.

Considerable difficulty has been experienced in making 110-volt heaters for tubes to be operated directly from the d.c. lines.
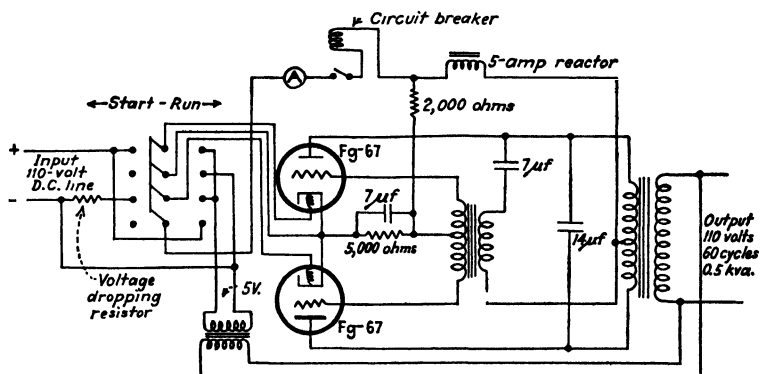
FIG. 67.—Method of heating filaments on direct current and then by a switch operating them from alternating current.

Therefore some method must be provided for heating the cathodes from alternating current. One of the most satisfactory sub-stitutes for a generator or other source of alternating current for heaters is the method shown in Fig. 67 consisting in heating the tubes initially from direct current, and then by means of a throw-over switch heating them from alternating current after the inverter has got into action. At the start the tube is heated through a series resistance; about 5 min. are required to start up the circuit.

The parallel-type inverter shown in Fig. 67 is designed to deliver 60 cycles, although the frequency may be changed by changing the 7-microfarad condenser shunted by the 5,000-ohm resistor. An approximate sine-wave output may be obtained by proper adjustment. A voltage regulation of plus or minus 10 per cent is obtainable by the use of proper grid and plate transformers.

The frequency will be maintained within 2 per cent from no load to full load.

The following bibliography (supplied by W. C. White) will give additional information on inversion.

LAUB, H., Discharge Tubes for Rectification, Inversion, and Frequency Changing (in German), *Elek. Masch.*, vol. 50, pp. 317–325, May 29, 1932.

HAFNER, H., Grid-controlled Mercury Valve Used as Rectifier and D.C.-A.C. Converter, *Bull. Oerlikon*, August-September, 1932, pp. 725–728.

Technical Principles and Applications of Controlled Rectifiers and Inverters (in German), *E.T.Z.*, vol. 53, pp. 770–786, Aug. 11, 1932.

PRINCE, D. C., Direct-current Transformer Utilizing Thyratron Tubes, *Gen. Elec. Rev.*, vol. 31, pp. 347–350, July, 1928.

Inverter for Projector Lamps (in German), *AEG Mitteilungen*, January, 1932, pp. 11–13.

WESTENDORP, W. F., An Inverter-lamp for the Conversion of 60-cycle Power into 1,000-cycle Modulated Light, *Phys.*, vol. 3, No. 4, pp. 193–202, October, 1932.

Gaseous Triode Commutator.—Many of the numerous circuits suggested for using gaseous triodes in conjunction with motors have been tested in the laboratory. Such tubes can be used with each of the four principal types of electric motor, *i.e.*, a d.c. commutator motor, squirrel-cage induction motor, a wound-rotor induction motor, and synchronous motor to produce a motor having new and very interesting characteristics. Dr. C. H. Willis[1] has described a machine having the construction of a synchronous motor but using grid-controlled rectifier tubes as a commutator. This forms a gas-tube commutation motor which may be operated on either direct or alternating current, and when operated on direct current it is much simpler in construction and has improved insulation over conventional d.c. machines. Operated from alternating current, the motor becomes an adjustable speed unit of great flexibility and high power factor. Operating from direct current, it has been necessary to provide two types of commutation, one for starting and the other for running conditions. The circuit in Fig. 68 represents a shunt char-

[1] WILLIS, C. H., A Study of the Thyratron Commutator Motor, *Gen. Elec. Rev.*, February, 1933, p. 76. See also WILLIS, C. H., Harmonic Commutation for Thyratron Inverters and Rectifiers, *Gen. Elec. Rev.*, December, 1932. See also E. F. W. ALEXANDERSON and A. H. MITTAG, Thyratron Motor, *Elec. Eng.*, November, 1934, p. 1517.

acteristic four-phase one-half wave gas-tube commutator motor. This method of starting commutation is independent of frequency and counter e.m.f. The starting resistances R_1 and R_2 are duplicates with tubes A' and C' connected to one resistance and tubes B' and D' connected to the other. The ends of these two resistances which connect to the tubes are joined through a condenser C_1, and the line connections to the resistances are
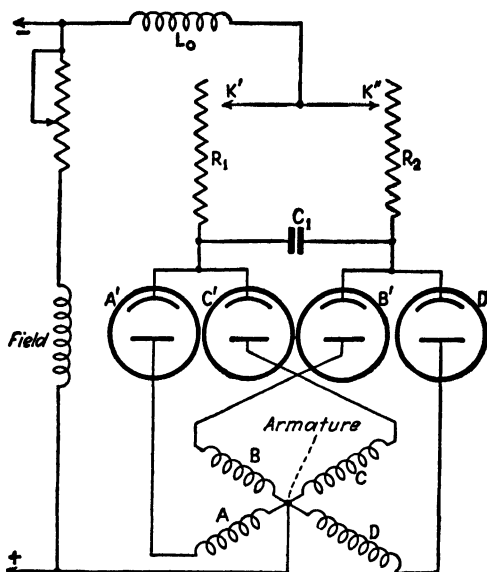
Fig. 68.—Circuit of tube commutator motor.

made through the movable starting contacts K' and K''. The grid circuit is controlled by a distributor driven synchronously by the motor, as shown in Fig. 69.

Upon closing the grid-supply circuit, that tube which is connected to a coil which is in position to produce the desired torque will be turned on. Assume that tube A' in Fig. 68 is thus made conducting. The initial current will flow partly through R_1 and partly through R_2 and the condenser C_1, to tube A'. In this way the condenser C_1 will be charged to a voltage equal to the voltage drop in resistance R_1 less the voltage drop in R_2. If the motor does not start, the current will finally be limited by resistance R_1; condenser C_1 will be charged to a potential E_0 or the supply voltage; and the motor will continue to produce the

torque corresponding to current I_0 which is limited by R_1. However, R_1 will be adjusted so that ample starting torque is provided. Now assume that the time constant of the R_2C_1 branch of the starting circuit is so short, as compared to the period of commutation, that the steady state is reached before the contact arm of the distributor shown in Fig. 69 moves from segment a to segment b. When the distributor contact arm moves from segment a to segment b, tube B will be made conducting; the current through the condenser C_1 will be reversed;
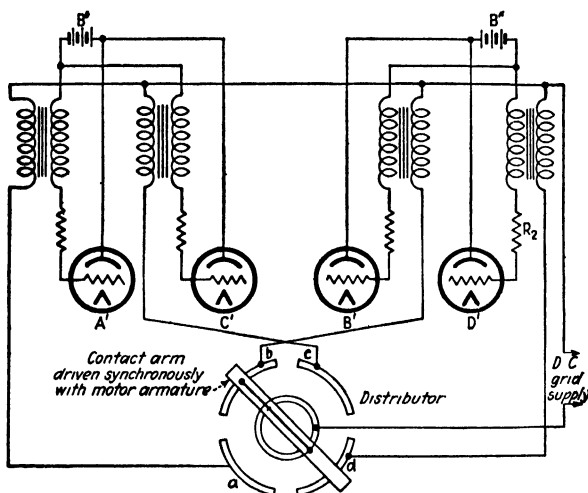
FIG. 69.—Distributor for providing grid control.

and an inverse voltage will be impressed upon tube A'. This inverse voltage on tube A' lasts for an interval approximately equal to twice the time constant of the starting circuit or twice the value of R_2C_1. As the motor comes up to speed, the starting resistances R_1, and R_2 are reduced proportionately and the voltage on the condenser C_1 is reduced as the motor counter e.m.f. increases. This causes a reduction in the commutating effect produced by C_1. Therefore, some different type of running commutation must be provided and in such a manner that as the starting commutation becomes less effective, the running commutation will become more effective, and thus the transition made progressively. When the starting resistance is completely cut out, the starting condenser C_1 is short-circuited and the tubes

are connected directly to the line. This type of starting com-
mutation has been found quite satisfactory.

The method of commutation employed for running, described
in this reference, is operative over wide ranges of load and fre-
quency variation with a constant counter e.m.f. Tube com-
mutation permits unconventional solutions of the problem of
commutation of the type of motor under consideration. Brush
problems are simplified. The greatest advantage offered by the
electron-tube commutator motor operating from direct current
resides in the fact that the commutator can be removed from the
motor and can be located at any convenient place. The motor
can have a rotating field with consequent improvement in arma-
ture insulation.

When operated from alternating current, the tubes act as
combined rectifiers and motor commutators. The advantage
on alternating current lies in the simplicity of reversal apparently
requiring much less equipment than more conventional methods.
For many applications, the great advantage will be the possi-
bility of using a stationary commutator located at some distance
from the motor, combined with the simple synchronous-motor
type of construction with a rotating field.

An electric motor having a stationary commutator with the
characteristics of a d.c. machine operating from alternating
current through grid-controlled rectifiers has been described by
E. F. W. Alexanderson and A. H. Mittag. A motor of this
type, intended for driving an induced-draft fan, has been built.
It is rated 400 hp. at 625 r.p.m. and 75 hp. at 350 r.p.m. These
are the specified ranges of horsepower and speed for the particular
application, although the motor may be successfully controlled
down to standstill, if required. The equipment operates from a
2,300-volt, three-phase, 60-cycle power supply.

Among the features of this motor are the following:

    1. While running from alternating current, it has the charac-
teristics of a series-type d c. machine.

    2. The speed of the motor is independent of the frequency of
the power supply.

    3. Smooth control of the speed can be obtained over the full
range.

    4. In the event of a momentary interruption of the supply
circuit, the motor will, upon the restoration of power, start and

return to the speed at which it was previously operating, without drawing excessive current from the line.

5. The efficiency is high, and the efficiency curve relatively flat—a distinct advantage, particularly in the lower portion of the speed range.

Motors of this type are applicable to such auxiliaries as fans, centrifugal pumps, compressors, and similar equipment having load characteristics such that the series type of motor can be used to advantage.

The motor has a stationary armature and a revolving field of the type used in synchronous motors. The armature, however, is provided with a special winding. Unidirectional current is supplied by means of a group of full-wave rectifiers which operate from the three-phase, 60-cycle current source. Power is supplied to the motor windings in the proper sequence and amount necessary to give the required torque for operation. This control is obtained by means of a small distributor mounted on one end of the motor shaft. Speed control is obtained by varying the voltage supplied to the motor armature, by means of a phase-shifting device acting upon the grids in the tubes. Through this method it is possible to obtain smooth speed control over the entire range for which the motor is designed.

The revolving field of the motor is connected in series with the neutrals of the armature windings, and, as a result, the motor has the characteristics of the well-known series-type d.c. motor.

The tubes perform the functions of commutation and grid-controlled rectification. Through the commutator function, the smooth, variable, speed-torque characteristics of a d.c. motor are obtainable, without any reference to synchronism with the power source used. The grid-controlled rectifier function provides the motor with continuous power control from standstill to maximum speed, without wasting power in resistance.

Illumination Control.—The grid-controlled rectifier operating through the medium of the saturable-core reactor has proved to be of considerable importance in the control of lighting whether for the stage, for show windows, for signs, for flood-lighting exteriors of buildings or other out-of-door objects, and for the interior decoration of assembly halls, roof gardens, etc.

Such uses of electron tubes seem to offer unlimited possibilities in the art of decorative lighting. By dimming and mixing the

primary colors in any desired sequence, a stage may be bathed
in any hue of the rainbow, and these hues may be changed at the
will of the set designer. Delicate pastel shades obtainable in
no other way are possible by the proper mixing of colors obtained
from banks of lamps of three colors.

The change in color can be effected by an operator at con-
siderable distance from the object to be illuminated, or it may be
done automatically by a presetting arrangement. Use of tubes
and their associated saturable-core reactor effects considerable
saving in power over a straight resistance variation method.

The maximum variation of the voltage of incandescent lamps
to be effective is from maximum to 20 per cent of maximum, or
for Mazda C lamps from maximum current to 39 per cent of
maximum. In case the lamps are directly visible, greater
variation is necessary; in this case the minimum voltage may
be as low as 8 per cent or the current may go as low as 22
per cent.

In controlling lamp intensity by resistance, much power is
wasted in the control rheostats. For example, if the load current
is reduced to 20 per cent, 92 per cent of the total power taken
is being wasted in the rheostats. Under the same conditions the
electron-tube-controlled equipment would be 30 per cent efficient.
The purpose of the rheostat in the older equipment is to reduce
the proportion of power taken by the lamps. Thus the rheostat
acts as a losser, all the power being consumed in the lamps at
full brilliance and none of the power going into the resistances.
At lower intensity, some of the power goes into the resistance
and the remainder into the lamps.

In tube-controlled equipment a saturable core reactor has two
windings: an a.c. winding in series with the line and the lamps
and a d.c. winding. As the current through the d.c. winding
varies, the impedance of the transformer varies, and more or
less current is permitted to flow from the line to the lamps. The
variable d.c. current is secured from the anode circuits of con-
trolled rectifiers. These controlled rectifiers pass more or less
average current through the cycle as the phase of their grids is
varied, by hand or by motor, with respect to the anodes. Since
the reactors are highly efficient, they have but little heat to
dissipate; and not only is power saved over the resistance
method, but long life may be expected of the reactors. Very

little power is consumed by the grids of the tubes or by the apparatus which varies their phase with respect to the anode.

In a typical installation two buttons control the direction of rotation of a small electric motor which changes the position of an iron core in a small solenoid-type inductor, thus varying the impedance of the solenoid and consequently varying the voltage drop across it. The adjustable voltage from this motor-operated inductor controls the flow of anode d.c. current through the saturable reactor.

For each bank of lamps to be controlled there is a panel of three tubes, a two-element gaseous rectifier, a controlled rectifier,
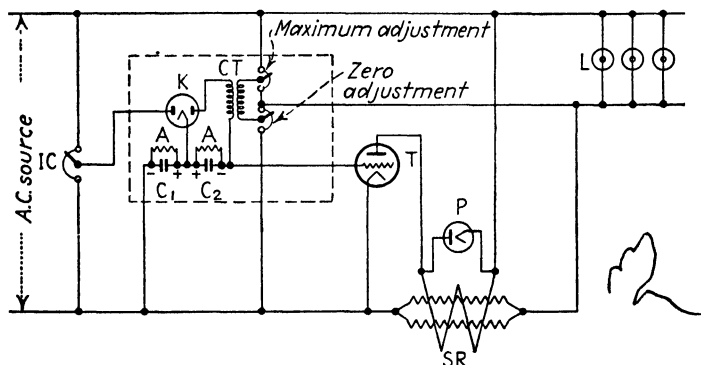
Fig. 70.—Feed-back circuit used in illumination control.

and in the system to be described below (known as the "feed-back" system of the General Electric Company) a full-wave, high-vacuum rectifier. The gaseous rectifier is used to permit current to flow during the interval between pulses of current supplied by the controlled rectifier.

The Feed-back Circuit.—In Fig. 70 tube T (the controlled rectifier) supplies power in pulses to the d.c. winding of the saturable-core reactor SR. Then, during the half cycle when T cannot pass current, since it is a rectifier, the energy in the saturable-core inductance forces current through the mercury-vapor tube P; thus, full-wave rectified current flows in the d.c. winding of the reactor.

The amount of current flowing in the d.c. winding is governed by the voltage supplied to the grid of the controlled rectifier tube from the feed-back circuit indicated in Fig. 70 by the diagram within the dotted lines. A remotely located intensity

control, usually an inductor but here represented by the potentiometer IC, produces a voltage whose magnitude may be varied but whose phase is of no consequence, since the two-electrode, high-vacuum tube K rectifies this voltage and charges capacitor C_1. The voltage across C_1, for any given input from IC, is practically constant because of the long time constant of C_1 and its discharge resistor A in comparison with the supply-system frequency. If, at the instant under discussion, C_2 is assigned a zero charge, the voltage existing across C_1 carries the grid of T positive, and the latter tends to pass maximum current.

This increases the saturation of the d.c. winding of the reactor, causing its impedance to decrease and the lamp voltage to rise. With the rise in lamp voltage, the control transformer CT, which is in effect connected across the lamp bank, charges C_2. The polarity of the voltage across C_2 is opposite to that across C_1. Hence, if the voltage of C_2 rises sufficiently high, the net voltage applied to the grid of the tube T is negative, and T will cease to pass current, thus causing the lamp voltage to drop.

Because the time constant of C_2 and its discharge resistor is nearly comparable to a half cycle of the system frequency, there is produced in effect an a.c. voltage superimposed upon the difference between the two d.c. voltages across the capacitors. The phase of this a.c. voltage is such that as its axis is shifted by a change in the value of the difference between the d.c. voltages, the phase angle at which it intersects the critical grid voltage of the controlled rectifier is shifted, thus producing phase control of the latter. Hence, as the lamp voltage nears the correct value, the tube regulates and finally passes the correct value of current to hold the lamp voltage at the desired value.

Potentiometers are provided to adjust the circuits properly when the intensity control is set at maximum and at zero. These adjustments are made easily at the time of installation and are fixed thereafter.

The feed-back circuit compares the voltage on the lamps with the voltage from the intensity control and acts on the grid of the controlled rectifier to hold the lamp voltage constant for any one setting of the intensity control. The feed-back effect results in the following advantages:

1. The lamp load may be changed through wide ranges without affecting the lamp-circuit voltage.

2. The variations of characteristics of tubes or saturable-core reactors are compensated by the circuit with respect to their effect upon lamp voltage.

3. The a. c. circuit is fast in operation compared to other reactor-type dimmers, since the controlled rectifier passes full or zero current except when the lamp voltage is near the correct value and thus produces a forcing action.

4. Since the feed-back circuit responds to the magnitude only of the voltage from the intensity control, and the phase of the voltage has no effect, the intensity control may be connected to a single phase of the power supply while the load is distributed over three phases.

5. Since the circuit responds to a change in voltage magnitude involving but little power, the intensity control can be placed at a remote point and connected to the rest of the equipment by means of a small cable.

Economics.—Recent advances in circuit and reactor design have made possible the use of tubes of lower rating than previously used, and this has resulted in a reduction in first cost, tube-replacement cost, and power loss. A program of standardization now underway tends to reduce to a minimum the number of types of component parts (such as tube panels, control units, etc.) needed in various combinations to meet the requirements of the many different specific applications. This will permit manufacture of component assemblies in economical quantities, reduce requisition development expense, and expedite shipment. This program of standardization is expected to be particularly helpful in the case of equipments for small theaters and auditoriums, and an increase in business in this large field is expected.

One of the principal benefits to be realized by the use of tube-reactor control instead of the inefficient resistance dimmer is a substantial power saving. Figure 71 shows the efficiency of the system for an 8-kva. reactor and may be considered typical for approximate calculations. The efficiency is a little higher with larger reactors and lower with smaller reactors. The curve also shows the power saved by using the tube-reactor system instead of a resistance dimmer, the kilowatt savings over resistance control, etc.

Economy may be divided into several headings such as power savings, reduced maintenance, space saving, etc. Regarding power savings, a great deal has been said about resistance losses. Compared with resistance dimming, it has been determined that a thyratron reactor type of control operating an 8-kw. load at 0.5

dimmer position 10 hr. per day for one year would save $236 with power based on 4 cents a kilowatt-hour. Losses in the tubes and their associated control apparatus including the coil of a contactor were included. An 8-kw. reactor with its control has an efficiency varying from 80 per cent at 30 per cent lamp volts to 96.5 per cent at 100 per cent lamp voltage. Economy in maintenance has been touched on previously in this discussion. Economy of space, particularly space on the stage, is an important factor, and here the all-electrical system shows up to advantage. For example, the Radio City Music Hall pilot controller with 313 circuits each with five scene presets plus scene masters, auxiliary master, group masters, color masters, grand masters, and an elaborate switching control for boomerang spots is only 16 feet long, 5 feet 4 inches high, and 4 feet deep.

Several large installations of this type of equipment have been made. The Radio City outfit has 328 circuits; that at the Metropolitan Opera House, New York, has 171, the Chicago Civic Opera has 147; and a recent installation at Mexico City has 70 circuits.

Fig. 71.—Comparative data, tube-controlled versus resistance-controlled dimmers (8-kva. reactor).

Electron-tube Control of Welding.—The application of grid-controlled rectifiers to welding is, at present, one of the most important of all uses of electron tubes. In this art there are difficulties which the complete control attained in the circuits to be described seems to have overcome in a manner not possible with other apparatus.

In line or seam welding the parts are held between electrodes in the form of rollers or disks of copper or copper alloy. The electric resistance between the two parts being welded causes generation of heat when a heavy current is passed through them from one roller to the other.

In the case of the continuously applied current for seam or line weld, a relatively large amount of heat is required at the start. As the work progresses, however, the heat will travel ahead of the point of contact on the rollers and less heat will be required. Also, if adjustments are made so that a good weld will be formed for the thickest portion of the material being welded, this heat may be too great for the thin section and burning may result. In some cases, the current will not follow along to form a continuous weld. The current will tend to follow the path of least resistance, and, if there are any high-resistance spots in the path of the electrode, it may skip such spots, giving imperfect weld.

Many of these difficulties can be overcome if the current is applied not continuously but intermittently during the progress of the work between the roll. By this means the line or seam weld becomes a series of overlapping spot welds. The metal chills between each spot and there is no building up of heat as the work proceeds. A voltage high enough to break down the resistance of the joints is momentarily applied forcing the current through the parts being welded.

It is often necessary to interrupt the line current several hundred times per minute to obtain the overlapping spot welds when the work is traveling at a speed sufficiently high to meet production requirements. Mechanically or magnetically operated circuit-interrupting devices have been used to obtain the interruptions. Such devices suffer from pitted contacts, high maintenance cost, frequent periods of being out of service for replacement and repair, as well as irregularity in timing by the mechanical switch.

In intermittent line weldings, the time that current is applied to the work and the ratio of time "on" to time "off" are factors of utmost importance. Any mechanical device is subject to a change of action depending on wear, friction, temperature and other variables. Changes from slow to fast operation of the timer also affect the accuracy. Accuracy of timing cannot be obtained in welding with an "on" period of only a few cycles unless the circuit-interrupting device is synchronized with the welding power supply. Such synchronism between a mechanical interrupter and the frequency of the power system is difficult to attain and to hold.

Electron-tube control of resistance line welding permits operation at a greater number of interruptions per minute than is possible with mechanical circuit-interrupting devices. There are two essential parts of such a circuit: the part which controls the welding current, and the part which controls the frequency and duration of time the current is permitted to flow.

In the tube synchronous timer (General Electric) the time "on" and time "off" are controlled accurately in synchronism
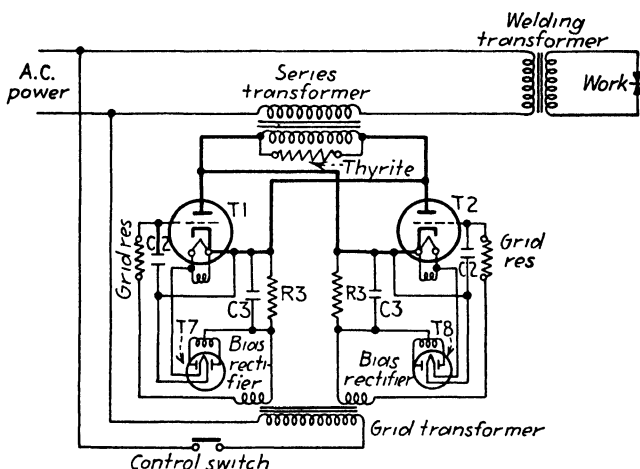
Fig. 72.—Typical welding circuit using controlled rectifiers.

with the frequency of the power supply. There are no make-and-break contacts or moving parts in the power line or in the equipment which controls the duration of the welding time. All moving parts and contacts in the equipment are associated with the adjustment; when they are set for a particular service, they remain stationary until a change in the welding cycle is desired. The adjustment is a simple process and the equipment is extremely simple.

Principle of Operation.—The circuit used in the tube control of welding is shown in Fig. 72. In series with the welding transformer[1] is another transformer whose secondary can be effectively open-circuited or short-circuited at desired intervals. When the secondary is open, the primary imposes considerable reactance in series with the welding transformer and little current will flow. (Actually some current will flow—that due the exciting current—

[1] See U. S. patent 1,935,413.

but this is insufficient to perform any of the welding operation.) When the secondary is short-circuited, the impedance of the primary is very low, and full current flows, impressing 95 per cent of the line voltage on the welding transformer.

It is necessary to use a series transformer because the tubes are high-voltage, low-current devices, and by the high-voltage secondary winding the necessary reduction in current is obtained. The action is similar to that of a current transformer.

When tubes 1 and 2 are conducting, the impedance of the primary of the series transformer is very low, so that practically full voltage is applied to the welding transformer. The only loss of voltage is that caused by the short-circuit impedance, which is approximately 4 per cent.

When the power tubes are not conducting, the secondary of the series transformer is open-circuited, and the primary current is only the exciting current of this transformer, which is about 4 per cent or less. By suitable grid control, the tubes can be made to conduct or not conduct, so that the duration of the welding current during the welding operation is governed by the action of these tubes.

Figure 72 shows the circuit with the transformers arranged for welding. The control switch should be considered a mechanical switch only for the explanation of this part of the circuit. With the switch open the only voltage on the grid of the power tubes is in the d.c. bias voltage furnished by the bias rectifier. With the control switch closed, the power tubes are turned on by adding a sine wave of grid voltage in phase with the anode voltage. Thus it is possible to turn the power tubes on and off by means of a comparatively small amount of power through the control switch.

It will be noted that the thyrite is connected across the high-voltage winding of the series transformer. This is for the purpose of keeping to a safe value the surge voltage generated by switching in the welding circuit, either primary or secondary. That is, if the power switch or line contactor bounces on closing, a high-voltage surge may be generated in the series transformer, and the power tubes may be fired by exceeding the allowable voltage. The same condition may exist when the electrodes are brought in contact with the work. The thyrite acts as a high resistance to the normal voltage but as a much lower resistance to the high

voltage; it thus absorbs the energy in current at comparatively low voltage rather than allowing the current to generate a high voltage in an effort to dissipate the energy.

The two capacitors between the grid and cathode of the power tubes are for the purpose of virtually tying the grid to the cathode at radio frequency rather than letting it assume a potential according to the internal capacity of the tube. That is, assuming equal capacity between the grid and cathode and the grid and anode, the grid would assume a voltage half that of the anode.
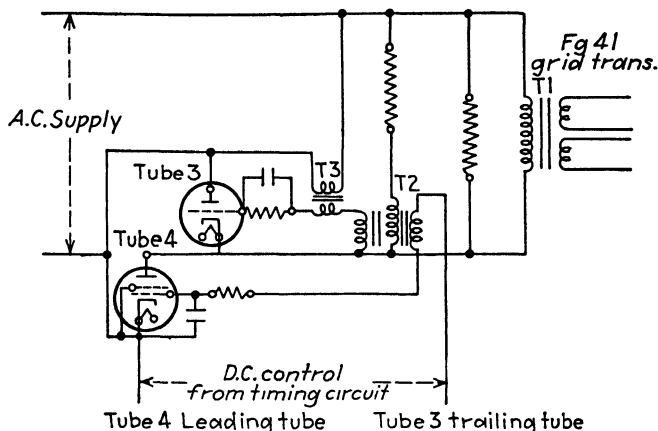
FIG. 73.—Intermediate control circuit for welding timer.

The impedance of these two capacities to 60-cycle power is so high that it can be neglected with reasonably low-impedance grid circuit; but for surges involving high frequencies, the impedance is much lower and actually causes the tubes to fire even though the anode voltage may not exceed the rating of the tube.

Operation of the Control Circuit.—To realize the maximum benefit from the use of tubes in the power-control circuit, the grid circuit should be controlled more accurately than can be done by a mechanical switch. Figure 73 shows an intermediate control circuit as used on tube-welder control panels equipped with tube timers.

The power to the FG-41 grid transformer is controlled by means of two small controlled rectifiers. These two tubes as shown in Fig. 73 are connected in such a manner as to allow one of them to pass one-half wave, and the other the opposite half wave. Thus,

by means of two half-wave rectifiers full wave power is applied to the grid transformers supplying the FG-41 tubes.

To avoid the necessity of controlling both tubes from the tube timer, one tube is made a "trailing" tube. By this is meant that the grid circuit of the trailing tube is arranged in such a manner as to cause it to fire immediately after the controlled tube. By means of such a circuit it is impossible to get other than full cycles to the grids of the FG-41 power tubes. This circuit decreases the load on the timing circuit because only one grid need be excited. A four-element, screen-grid controlled rectifier is used in the leading or ratio tube, still further increasing the economy of grid excitation.

Tube 3 is normally nonconducting because an a.c. voltage is applied to its grid 180 deg. out of phase with the anode. Grid rectification is utilized to furnish a bias to the triode. Thus the tube will be nonconducting regardless of small changes in the phase of the anode voltage. Tube 4 conducts or not depending upon the d.c. voltage derived from the control circuit.

Transformer T_2 has a primary designed to operate at about one-fourth that of the a.c. supply voltage and has a voltage-dropping resistance in series with it across the line. This transformer saturates early in the a.c. cycle, and for this reason its secondary voltages have a peaked wave shape. The secondary winding in series with the grid of tube 3 has such a polarity that it fires tube 3 immediately after current from tube 4 passes into T_1. Because of the sharpness of this firing wave, tube 3 fires at this point in the cycle or not at all. Tube 4 is fired through its winding of transformer T_2 at the beginning of the wave or not at all. The low voltage delivered by this winding does not affect the control point of tube 4 but merely supplies alternating current to the grid transformer during the conducting period.

The Timing Circuit.—Figure 74 gives the timing circuit for this type of welder (General Electric). The grid of the tube is returned to a slightly positive point of the system for the steady-state condition. The transformer TR_4 gives peaked waves, the peak occurring at the power-factor angle of a welding transformer. When direct current is supplied, the instantaneous voltage across C_1 is zero, and the entire d.c. voltage drop of the line occurs across R_1, because of the voltage lag in a condenser. Furthermore, the voltage across the tube is zero (anode to

cathode), but the grid will be 250 volts negative except for the small peaked voltage and the drop across R_3.

The condenser starts to charge, however, and builds up along an exponential curve, the slope depending upon C_1 and R_1. When the tube fires, C_1 is discharged through the inductance in the anode circuit. When the field about this inductance collapses, it charges the condenser in the opposite direction to stop conduction again. The process is now back at the starting point with the condenser discharged and ready to be charged through R_1 and R_5 from the d.c. supply.

R2 Ratio potentiometer   X2 Commutating inductance
R1 Timing resistor   TR4 Synchronizing transformer
C1 Timing capacitor   T1 Timing tube
R5 Current limiting resistor
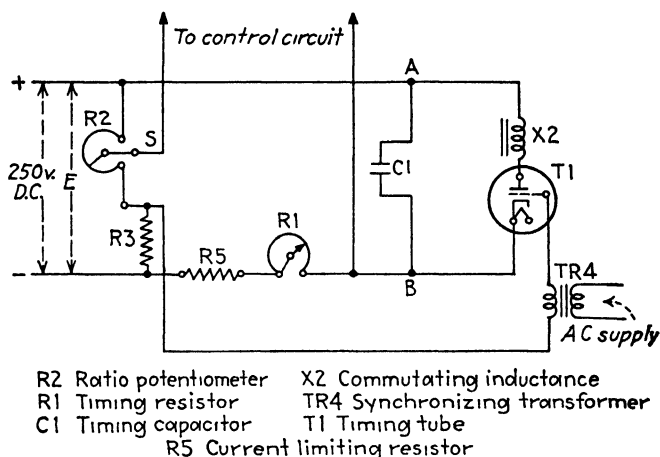
Fig. 74.—Timing circuit used in welding control.

The elapsed time between successive condenser charges is controlled by C_1 and R_1. Because of the peaked synchronizing voltage, the time will always be a given number of cycles.

The controlling voltage from this circuit is taken as shown in the diagram from point B and from the movable arm on the potentiometer R_2.

The "Lock-out" Circuit.—General Electric has a circuit that is designed especially for spot welding where it is necessary to arrange the control so that the timing circuit cannot make more than a single oscillation as described above. The grid of tube 1 is made negative by several volts. Tube 6 pulls this tube's grid negative by about 100 volts. Instead of a reactor in the anode circuit of tube 1 as in the previous circuit, a high leakage reactance transformer is used. The grid of tube 6 is connected

to a point about 20 volts negative through the secondary of this transformer. This tube will continue to conduct, once fired, until short-circuited by Sw_3.

If, then, the switch has been closed and then opened, the grid of tube 1 has the potential of point W except for the peaked voltage supplied by TR_4. The point W is fixed so that tube 1 is conducting except for the peaks of the waves of TR_4. After the first positive peak has fired tube 1, which initiates the timing circuit described above, but through TR_6, tube 6 is given a

FIG. 75.—"Lock-out" circuit for spot welding for single-cycle welds.

positive voltage, and it at once fires. Current flowing through R_6 pulls the grid of tube 1 negative by 100 volts and stops conduction there. Therefore one cycle has been permitted, but the timing circuit cannot be fired again because tube 6 conducts until it is actually short-circuited by Sw_3.

Half-cycle Welding Circuits.—A simple circuit where the contactor is replaced by a single tube, thus restricting the welding times to one-half cycle or less is shown schematically in Fig. 76 and is used in welding (spot or resistance) vacuum-tube parts.[1]

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[1] GRIFFITH, R. C., *Gen. Elec. Rev.*, September, 1930. See also MARTIN, SAMUEL, JR., *Welding*, May and June, 1932.

In the circuit, tube T_1 replaces the contactor and T_2 controls the grid of T_1. In the "off" position, T_2 is conducting and the d.c. negative bias on T_1 is equal to the voltage drop across resistor R_3. An a.c. bias, leading by approximately 160 deg. and supplied by transformer Tr_3 from the phase-shifting circuit composed of
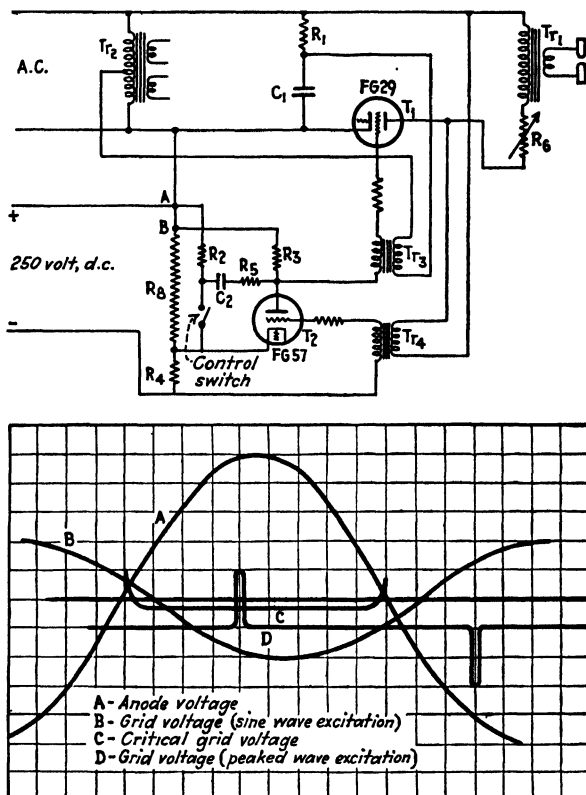
FIG. 76.—One-tube welding circuit. T_2 controls T_1, which controls the weld.

capacitor C_1, resistor R_1, and the primary center-tap of transformer Tr_2, is also impressed on the grid of T_1. This bias has no function in the "off" position. With T_2 conducting and the control switch open, the capacitor C_2 is charged through resistors R_2, R_5, and T_2 to a voltage approximately equal to the voltage across R_3 and of a polarity such that the terminal connected to the anode of T_2 through resistor R_5 is negative. Closing the control switch to make a weld connects the positively charged

terminal of capacitor C_2 to the cathode of T_2 and the anode of T_2 is drawn negative for a time long enough to commutate this tube. Capacitor C_2 then discharges through resistors R_5 and R_3 and recharges through these resistors to the reverse polarity. When C_2 has become very nearly charged to this new polarity, the voltage drop across R_3 is low and thus T_1 has practically no d.c. bias. As the d.c. bias approaches *zero*, a condition is finally reached as shown on Fig. 76. Curve A represents the anode voltage of tube T_1, curve B the a.c. grid voltage, and curve C the critical grid voltage. With zero d.c. bias the curves show that due to the a.c. grid voltage leading the anode voltage by 167 deg. there is only a 24-deg. firing angle. This means that if the d.c. bias is sufficient to hold T_1 off for the first 24 deg. of the positive half cycle, it will not "fire," even though the d.c. bias drops to zero immediately afterward, until the beginning of the next positive half cycle. Tube T_1 then carries current for practically the full half cycle or not at all. (If it is desired to have the firing angle smaller, the a.c. grid voltage may be increased and the phase of this voltage advanced until it is within a few degrees of 180 deg. leading.) The firing of T_1 excites the primary of the welder transformer and refires T_2 by the voltage impressed on the grid of T_2 through transformer Tr_4, biasing T_1 off before the start of the next positive half cycle. Opening the control switch allows capacitor C_2 to recharge to the correct polarity for commutation of tube T_2 upon closing this switch for making the next weld. The current flowing during the welding period may be set by variable resistor R_6.

If it is desired to weld in periods adjustable to one-half cycle or less, the circuit of Fig. 76 may be used by inserting a resistor between points A and B, which changes the method of controlling the grid of the tube T_1. The bias is reduced by commutation of T_2 to the voltage drop across this resistor instead of zero, and the peaked a.c. grid voltage from peaking transformer Tr_3 is of sufficient magnitude to overcome the reduced bias and fire T_1. Curve D of Fig. 76 illustrates this type of grid excitation in the "firing" position. Shifting the phase of the grid-transformer primary voltage by varying R_1 shifts the position of the peak, in this way controlling the length of the conducting period.[1]

[1] LORD, H. W., and O. W. LIVINGSTON, Thyratron Control of Welding in Tube Manufacture, *Electronics*, June, 1933.

Another half-cycle circuit using a pool-type (igniter) controlled rectifier is given in Fig. 77. In this General Electric circuit the tube and the primary of the welding transformer are in series across the line, in the conventional fashion. The 80-type rectifier furnishes direct current across C_1. A voltage divider placed across C_1 with the glow tube provides voltages to the control tube FG-57. Transformer TR_2 has a characteristic such that it saturates so that the output voltage is peaked in form near the normal zero point of the voltage wave.

Normally, the FG-57 does not pass current because of the negative voltage on its grid from the voltage divider. When the operator's control switch is closed to the down position, the condenser C_2 is ready to be discharged, and the cathode of the FG-57 is connected to a point such that the grid bias is somewhat less negative. The magnitude of the peaked voltage in TR_2 is now sufficient to overcome the negative voltage across the glow tube. When the first peak voltage occurs after the switch is closed down, the condenser C_2 discharges

Fig. 77.—Half-cycle circuit using igniter tube

through transformer TR_3, impressing a voltage on the starting electrode of the pool-type rectifier. The phase relations are such that this tube then passes current, its anode being positive. When the switch is released, C_2 recharges for the next weld.

Pool-type Tube Spot Welder.—In Fig. 78 is the elementary diagram of a spot welder available in several forms (General Electric) depending upon the amount of power to be handled. Direct current for timing and control is furnished by a conventional full-wave rectifier-filter system. In addition, there is a keying tube, to insure starting at the desired point on the voltage wave after the closing of the control switch, the timing

as well as the leading control tube, the trailing tube, and the power tubes.

Across the filter is a voltage divider R_1 limiting the minimum bias that can be placed on the timing tube and preventing any extension of the time beyond the steep part of the capacitor charge curve. R_2, a variable resistor, controls the timing or length of spot by controlling the bias on the timing tube. R_3 provides the negative bias for the keying tube to hold it non-conducting except for the duration of the peak voltage furnished by the peaked wave transformer.
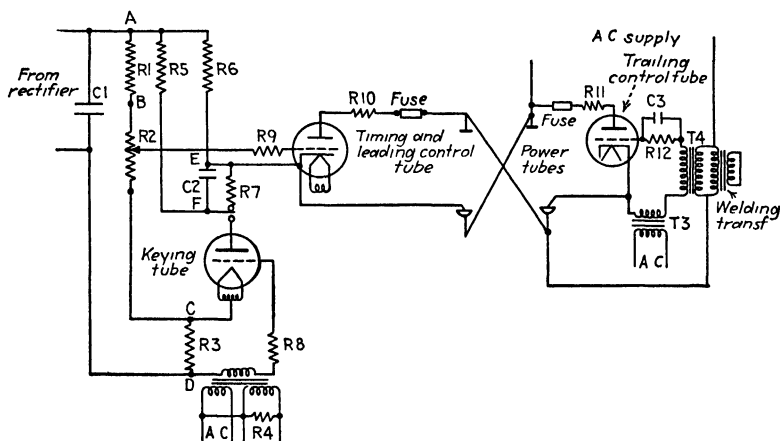
Fig. 78.—Spot welder with control circuits.

The keying-tube grid bias holds this tube nonconducting except for 5 deg. on the a.c. wave once each cycle. The point at which this 5 deg. occurs is controlled by R_4. When a spot is to be made, the switch closes the anode circuit of the keying tube. Since the anode voltage is direct current, the tube on the first positive peak after closing the switch will conduct and continue to conduct until the switch is opened. When the switch is closed and the tube breaks down, point F becomes at the same potential as point C except for the small voltage drop through the tube (15 volts). Because of the time delay in building up the voltage across a capacitor, point E is momentarily at the same potential as C except for this same tube-voltage drop. Therefore the voltage across A and C appears across R_6 at this same instant.

Capacitor C_2 starts to charge, and point E is gradually elevated towards A until C_2 is fully charged and there will be no drop

across R_6. R_5 is connected across R_6 and C_2 to draw sufficient current to keep the keying tube ionized after C_2 is charged.

The grid circuit of the timing and leading control tube is connected between the slider on resistor R_2 and point E. With the control switch in its normal position, with resistor R_7 short-circuiting capacitor C_2, and no current flowing in R_6, point E will be the same as A, and the bias on the timer tube will be negative and consist of the drop in R_1 plus that portion of R_2 included between B and the slider. Therefore, the timing tube will be nonconductive.

When the control switch is closed and the keying tube conducts, point E will be forced to the potential of C, and the bias on the timing tube will be positive by the portion of the voltage drop in R_2 included between the slider and C. Thus the timing tube conducts immediately as the voltages are arranged so that the keying tube starts as soon as the anode of the timing tube becomes positive. Point E rises from C toward A as C_2 charges; and when it gets positive of the slider by the amount of the critical voltage of the timing tube, this tube will cease to conduct, and the spot will be terminated. With the slider at the C end of R_2 the length of spot will be short.

The timing tube times as well as controls one of the power tubes. The other power tube is controlled by a tube identical with the timing-control tube but is held nonconducting with a self-rectified grid bias. The "trailing" control tube is made conductive by means of a feed-back transformer, the primary of which is connected across the welding transformer. The secondary is connected in the grid circuit in such a direction as to throw the grid positive during the last of the conduction period of the leading tube so that the trailing power tube will be made to follow and deliver the next half cycle to the welding transformer.

The power tubes (mercury-pool resistance starter type) are connected "back to back" to pass full-wave a.c. power. When the leading control tube is fired by the timing circuit, the corresponding power tube conducts and carries the line current of the welder for one half cycle until the line current goes through zero. At the time of zero current, there will be considerable line voltage, depending on the power factor of the load (the lower the power factor the higher the voltage). Therefore when the

leading tube ceases to conduct, the line voltage at that instant appears across the trailing power and control tubes. The grid of the control tube is made positive by the secondary of the feedback transformer T_4, which makes the control tube conduct and breaks down the corresponding power tube to carry the second half cycle of line current. Thus every time the leading tube is made to conduct, the necessary sequence follows to deliver a full cycle of power to the welder.

The trailing tube is normally held nonconductive by means of the secondary voltage of transformer T_3 which is arranged to be 180 deg. out of phase with the anode voltage on this tube. In addition to being 180 deg. out of phase, it is also given a slight d.c. component due to grid rectification which is filtered by means of capacitor C_3 and resistor R_{12}.

The welding-control circuits described here are the most complex and the most accurate now available. Simpler circuits have been developed and have been used where a high degree of accuracy of control is not necessary or where simplicity and lower cost are fundamental requirements. The Welding Timer Corporation has been successful in developing circuits that use ordinary radio-receiving tubes to operate power relays which in turn control the flow of welding power.

Voltage Regulation.—Grid-controlled rectifiers, and high-vacuum tubes, too, have been used rather extensively in circuits for voltage regulation. Only the more recent adaptations will be described here. A good example of the utility of the controlled rectifier for this type of application is the stabilizing of battery-charger rates in a utility substation.[1]

Operating practice in regard to station batteries at the substations and generating plants of Southern California Edison Company, Ltd., now calls for a floating charge which maintains the battery voltage at 2.15 volts per cell. At many of the stations the motor generators for charging the batteries are much larger than normally required to supply the floating charge in order that they may be capable of bringing the battery up in a reasonable time after a period of abnormal demand or an outage of the charging equipment. Consequently, under the normal floating-charge condition, the battery-charging generator is operating so low on its saturation curve that the charging rate is

[1] DOOLITTLE, F. B., *Elec. World*, Aug. 25, 1934.

unstable, requiring frequent adjustment of the field rheostat by the station operator. Various makeshifts have been used at some stations such as a vernier rheostat connected to the generator field rheostat or resistance in series with the generator armature which permits the generator to operate at a higher voltage at the expense of some energy loss.

The circuit in Fig. 79 shows how a gaseous tube was used to solve this difficulty. If the generator voltage drops considerably, the grid will become positive and will draw current from the grid battery, the amount of current being limited to a low value by the 25,000-ohm grid resistor.
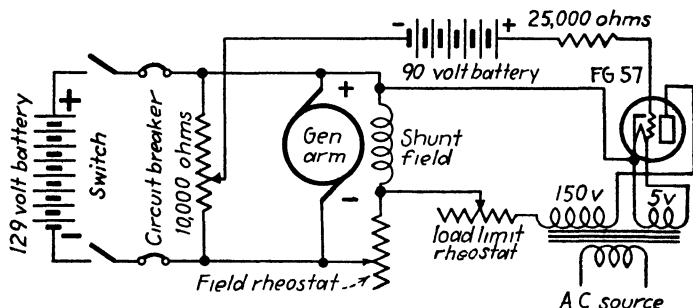
Fig. 79.—Voltage regulator for battery charging motor generator.

Current for the plate circuit of the rectifier tube is supplied by a 150-volt winding on a transformer which is supplied from the same source as the motor that drives the generator. During the half cycles when the tube is conducting, current flows from the 150-volt transformer winding through the tube from the plate to the cathode and thence to the positive end of the shunt field, where the current divides, part going through the field, tending to increase the generator excitation, and part through the generator load circuit and the field rheostat back to the load limiting rheostat and the transformer. Thus only a portion of the total rectifier current is available to increase the generator excitation, the proportion being determined by the relative resistances of the shunt field and of the field rheostat at the no-load or floating-charge setting. On the 6-kw., 150-volt machine to which this regulator was applied it was found that increasing the average field current 0.2 amp. increased the charging rate of the machine from 8 amp. floating charge to 40 amp., which is

full load on the machine.   The FG-57 tube used has an average
anode-current rating of 2.5 amp., so that as much as 2.3 amp.
of the rectified current could flow through the load and field
rheostat and still leave the 0.2 amp. required to obtain the desired
regulation of the generator.   As a matter of fact, the resistance
of the field winding and of the field rheostat is about the same
on this particular machine for the floating-charge setting of
8 amp. and 129 volts, and, consequently, a smaller tube capable
of carrying but 0.4 amp. would accomplish the desired regulation.

With the potentiometer set to hold 129 volts, the regulator
functions so perfectly that deviations from this voltage cannot
be detected on the switchboard voltmeter when any load within
the generator rating is thrown on the station battery circuit,
the generator immediately picking up current equivalent to that
taken by the additional load.   In case several large circuit
breakers are closed in succession, the battery voltage is pulled
down, and the generator picks up full load, maintaining it until
the battery voltage is again normal.   The constant load on the
battery at this station is 8 amp.   The field rheostat of the
generator is set to charge about 6 amp. without the regulator, so
that normally the regulator supplies a small part of the generator
excitation.

The circuit[1] of a grid-controlled rectifier voltage regulator is
shown in Fig. 80.   It has been successfully applied to a 12.5-kva.
60-cycle 220-volt alternator, supplying power to a laboratory
for precise thermal conductivity testing.   The requirements
were twofold; the action of the regulator had to be fast enough
that voltmeters and wattmeters could be easily read to 0.5
per cent without the operator having to judge the mean point
of wide fluctuations of the needle, and at the same time the voltage
had to be stable over periods of 48 hours or longer in order
that tests might attain complete thermal equilibrium.   The
voltage developed in the armature of the generator C is desired
to be controlled; therefore it is impressed through the auto-
transformer D and the phase-correcting resistance and con-
denser K and J upon the voltage-sensitive bridge circuit E-F.
E_1 and E_2 are carbon filament lamps having a negative tem-
perature coefficient of resistance and consequently a negative

[1] WEINLAND, *Rev. Sci. Instruments*, vol. 3, pp. 9–19, 1932.   See also
Electronics, April, 1932, for a short description of the equipment.

nonohmic resistance characteristic with changing voltage, while the behavior of the opposite arms of the bridge, which consist of ordinary Mazda lamps, is just the opposite. Consequently for any given set of lamps there is only one value of voltage at which the bridge will be balanced, while at any value above or below this point the unbalance of the bridge will be a function of the direction and magnitude of the deviation of the voltage from normal. The output of the bridge is put through audio transformer I to insulate the voltage-sensitive bridge from the grid
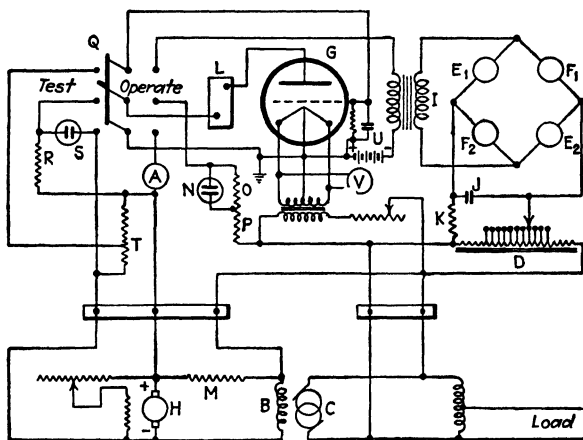
Fig. 80.—Gas triode voltage regulator.

circuit, and is then impressed upon the grid of the tube, a 0.1-megohm leak and a grid condenser being provided for stability.

Plate voltage is applied through O and P and the time delay relay L to tube G. The resistor M is in the field circuit of the generator, H being the exciter armature and B the generator field winding. The current from the tube during periods of operation passes through the resistor M in the same direction as the field current of the generator and builds up the voltage drop across the resistor, reducing the field current and reducing the voltage developed in C. Since the field rheostat of the exciter H is so set that if the tube did not operate, the voltage developed would be too high, intermittent operation of the tube is required to keep the voltage bucked down to the proper point.

As a test circuit when the switch Q is thrown to the "test" position, the plate of the tube is disconnected from the 220-volt

alternating current and connected instead to plus 125 volts direct current through the resistor R, while the grid of the tube is made positive by connection to the tapped resistor. A voltmeter plugged into the receptacle S will then read the voltage drop from plate to filament of the tube, and when this voltage is found to be rising rapidly at successive readings the indication is that the end of the life of the tube is near.

Variations in voltage of about 0.5 per cent only were caused by a load change of from 0 to 40 amp. and an excitation voltage change of from 120 to 145 volts.
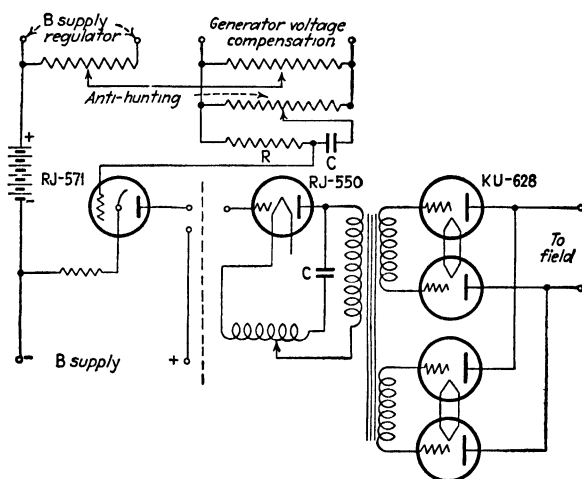
Fig. 81.—Regulator for a.c. generator.

Voltage Regulator for Alternating-current Generators—Westinghouse Type AT.

—This regulator uses the phase-shifting operation of a gaseous triode to control the exciter field current in an a.c. generator whose output is being regulated. The principle of operation is briefly as follows. The generator voltage is rectified by a full-wave rectifier tube and the filtered output is bucked by 90 volts from a battery. The resultant voltage is amplified (RJ-571) and the plate current of the final amplifier (RJ-550) controls the phase relationship between the grids and plates of the gas tubes in such a manner that the plate current will increase if the generator voltage decreases. Since this plate current controls the exciter field current, the device will keep the generator voltage output constant.

Antihunting is provided by applying the output of the exciter armature to a potentiometer. Whenever this voltage changes, a displacement current flows into a condenser C and the IR drop across a resistor R due to this current applies a bias to the control grid of the first amplifier tube. The polarity of the connections is such that this antihunting bias opposes corrective action by an amount proportional to the rate with which the action is becoming effective; so hunting is prevented.

The phase variation is produced by the varying current passed by the tube RJ-550 and the capacity C.
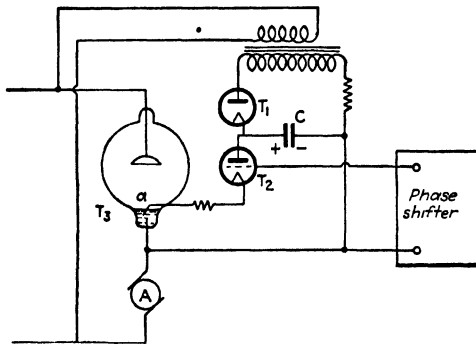
FIG. 82.—Ignitron speed-control circuit.

The type AT a.c.-voltage regulator is being used in testing incandescent lamps on alternating current where the lamp voltage must be maintained to within one-tenth of one per cent. Power is supplied by a 250-kva. single-phase 60-cycle 220-volt 1,200-r.p.m. generator, driven by a 375-hp. 2,200-volt synchronous motor. A separate $6\frac{1}{2}$-kw. 125-volt direct-connected exciter is controlled by the electronic equipment.[1]

Variable-speed Control Using Ignitron.—The characteristics of the ignitron have been described earlier in this book. In Fig. 82 is a circuit feeding the armature A of a d.c. motor for

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[1] See GULLIKSEN, F. H., *Elec. Eng.*, June, 1934, for a general discussion of several types of a.c. generator regulators using electron tubes. See also SPORN, PHILIP, and G. G. LANGDON, *Elec. World*, May 11, 1935, and BAKER, E. A., and H. A. BOLTZ, *Rev. Sci. Instruments*, January, 1936, p. 50, for the use of a gaseous-tube voltage regulator for the accurate measurement of the breakdown and current-voltage characteristics of liquid dielectrics. Currents from 10^{-16} to 10^{-3} amp. up to 40 kv. were measured.

variable-speed control.[1]   A single ignitron is shown for simplicity, though in general, full-wave rectification would be used. Here the condenser C is charged with the polarity shown during the half cycle of inverse potential on the tube.   The rectifier T_1 prevents this charge from reversing on the next half cycle during which the grid-controlled rectifier T_2 is biased to break down and discharge the condenser through the igniter electrode a. The point on the cycle at which this occurs may be varied by adjusting the phase of the grid voltage on the gaseous triode T_2. The average rectified output of the ignitron is thus varied in the well-known manner from a small value corresponding to breakdown at the end of the half cycle to a maximum value corresponding to breakdown at the beginning.

The author points out that when these tubes are developed to operate with control currents of an ampere or less, the phase-control circuit of Fig. 82 can be considerably simplified by the omission of the auxiliary tubes T_1 and T_2 as well as the condenser. The output of the phase shifter would be applied directly to the igniter electrode, for example, with a small copper oxide rectifier, to prevent back current through the igniter on the inverse cycle.

Constant-speed Direct-current Motor Operation from Alternating-current Source.—An electronic circuit (Westinghouse) has been developed for operating d.c. motors of 3 hp. or less, from a variable voltage source of alternating current.   The system supplies a constant d.c. voltage at any value between 100 and 550 volts from a single-phase a.c. source. Although the load may change from zero to maximum, the d.c. voltage is maintained constant between plus or minus 0.5 per cent, and in spite of variations in a.c. voltage between commercial limits, the maximum d.c.-current load is 10 amp. The controller has a rising characteristic with increasing load, which maintains the motor speed constant within 1 per cent from no load to full load for any speed between a 5 to 1 range.   A rectified voltage is supplied to the motor armature and field by the KU-623 controlled rectifiers after proper filtering produced by armature and field reactance.

By a phase-shift circuit composed of a condenser and the RJ-550 tubes, the angle between plate and grid voltages of the KU-623 tube varies the rectified current.   Thus a 0.1 volt change

[1] KNOWLES, D. D., *Electronics*, June, 1933.

on the first RJ-571 carries the current from the KU-623 between
zero and maximum. The field is in series with a rheostat across
the armature. The voltage across the field is smoothed by a
filter, and the voltage between the field and that supplied by a
dry-cell battery goes to the RJ-571 grid. This voltage difference
is maintained at 2.5 volts. The compensating circuit includes
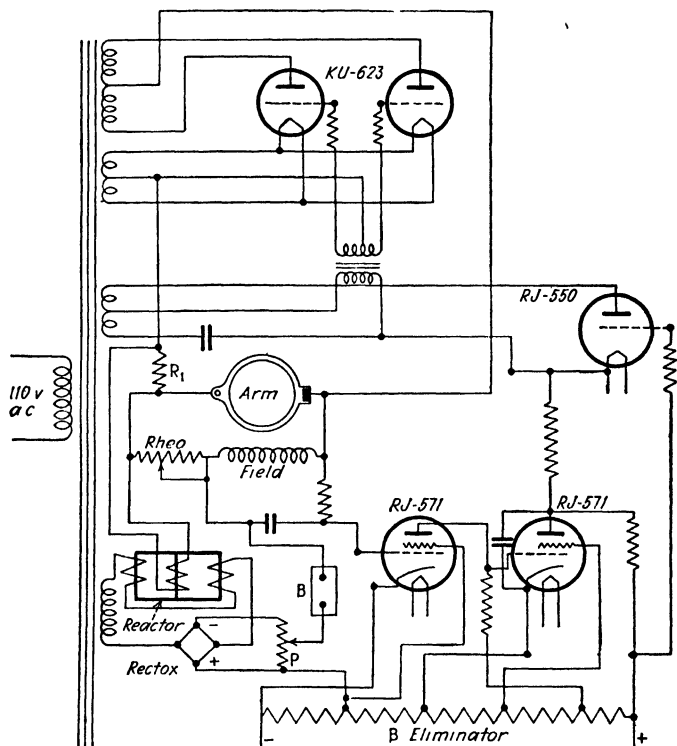
Fig. 83.—Circuit for operating d.c. motors from a.c. source. B is a dry-cell
battery.

a three-legged reactor in series with a copper oxide rectifier.
The d.c. winding shunted across R_1 is in series with the arma-
ture. The impedance of this reactance decreases as the current
through the d.c. winding increases, and therefore, the d.c. output
voltage of the rectifier increases with increasing motor load.

By the potentiometer P, a variable part of the Rectox voltage
is applied to the RJ-571 to maintain a constant balance bias on
the tube. Consequently, the field voltage and armature voltage

will be increased to maintain constant speed under a variable load.

Automatic Voltage Regulator.—Experiments with gas-tube-controlled voltage regulators have been reported by Austin and Cooper,[1] using the fundamental characteristics of an iron-cored reactor which has a changing voltage-current characteristic as saturation is approached. After experimenting with manual
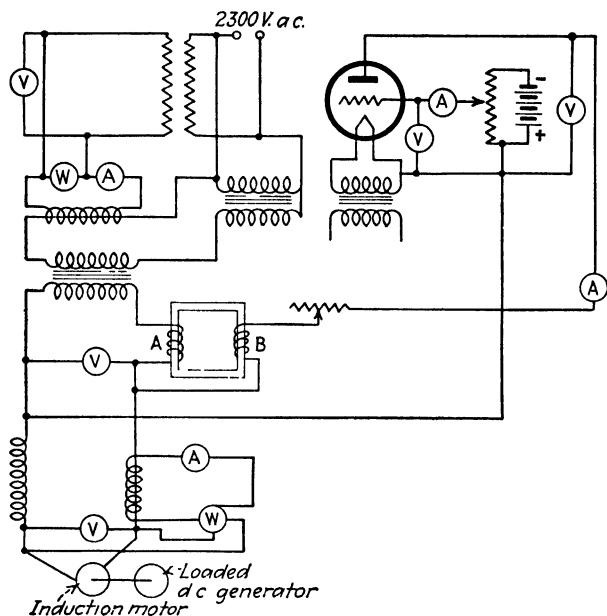
Fig. 84.—Preliminary stage of voltage-regulator development.

control, grid-controlled rectifiers were used as in Fig. 84 to effect an automatic control. The circuit consisted of a booster-connected 2,200- to 220-volt single-phase transformer taking power from a 2,300-volt line. The boosted voltage is then stepped down through another 2,200- to 220-volt transformer which supplies power through the regulating reactor and the reactive line to the load. The control coil *B* of the reactor is connected across the supply end of the feeder, in series with a rheostat and the plate circuit of the tube, an FG-67 grid-controlled rectifier.

[1] Austin, T. M., and F. W. Cooper, Application of Nonlinear Circuits, *Elec. Eng.*, February, 1934.

It was possible to effect entirely automatic regulation of the load voltage from no load to full load. Operation depended upon the variation in the induced voltage of coil *B* occasioned by variation in the load current flowing through the primary coil *A*. The voltage at the supply end of the feeder was connected in series with coil *B* to obtain sufficient operating voltage for the plate circuit of the tube. A range in plate voltage from 560 volts at no load to 460 volts at full load was obtained.
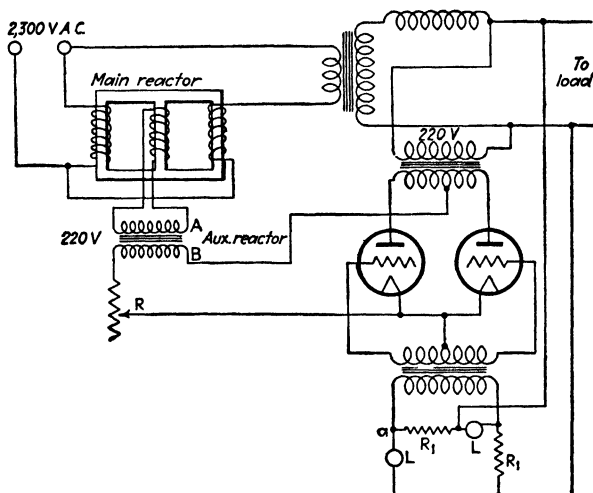
Fig. 85.—Use of three-legged reactor in voltage regulation.

Application of Three-legged Reactor.—The next step in the evolution of the regulator is shown in Fig. 85, where a three-legged core of a 13,200- to 220-volt three-phase transformer was used. The control current is passed through an auxiliary reactor *B*, the other coil of which was connected in series with the center coil of the main reactor. Control current for the auxiliary reactor was obtained by rectification from the load end of the line. The tube plate current is controlled by a voltage-sensitive bridge made up of resistances and tungsten filament lamps. These lamps have an equilibrium current which varies as the square root of the applied voltage. Thus a combination of linear impedances, the resistances, and nonlinear impedances, the lamps, forms a bridge such that only one terminal voltage exists which permits opposite points to have the same voltage. At this value no current flows through the primary transformer.

At this voltage the tubes are not in stable equilibrium. They conduct about half the time, to feed more direct current through coil *B*, decreasing the impedance of the secondary coil *A*, permitting more current to flow through the center coil of the three-legged reactor. This reduces the voltage drop in the outer coils and raises the load voltage.

The advantages of such a regulator are: absence of moving parts, no necessity for relays, elimination of hunting, noiseless operation, probably cheaper to manufacture than existing types of induction regulators.

Electronic Phase-failure Relay.—A useful application of the grid-controlled gaseous rectifier may be found in the phase-failure relay developed by Stansbury and Brown.[1] Not only is the apparatus designed around the principle useful; but the underlying theory is interesting and important.
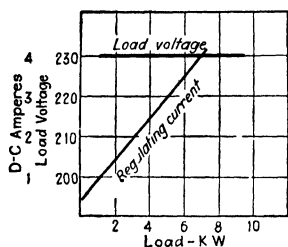
FIG. 86.—Control effected by Fig. 85.

The apparatus is an example of equipment that, employing electronic tubes, can compete with older equipment having the prestige of years of successful service.

Where a polyphase (generally three-phase) a.c. motor is used for driving an elevator or hoist, it is necessary to so arrange the controller as to prevent operation of the motor unless the supply-voltage conditions are correct. For instance, if the phase rotation of the supply is in the wrong direction (which may be the case due to switching or maintenance operations of the power-distribution system), the motor will run in the "up" direction when the handle is put in the "down" direction, and vice versa. Similarly dangerous conditions arise from failure of one of the supply lines, resulting in a single rather than multiphase supply.

The electronic relay described below is what may be termed the shunt type, which responds to the voltage conditions of the lines feeding the load, as contrasted with the series type of protection which responds to the current passing to load. The former type is suitable for applications like elevators where the motor is stopped frequently. If a single-phase condition occurs while the motor is running, voltage generated in the motor will hold up the voltage of the third line, preventing the relay from

[1] STANSBURY, C., and G. C. BROWN, *Electronics*, February, 1933.

functioning until the motor approaches rest. This is desirable in an elevator so that a landing can be reached before the equipment is shut down by the relay.

Figure 87 is an elementary diagram of the system. The tube is of the grid-controlled gas rectifier type. The method of control makes use of shifting the phase of the grid voltage with reference to the anode voltage. But, instead of using such phase-shift control in the way most commonly described, as a means of taking any portion of the half wave desired and thereby adjusting the r.m.s. current, advantage is here taken of the fact
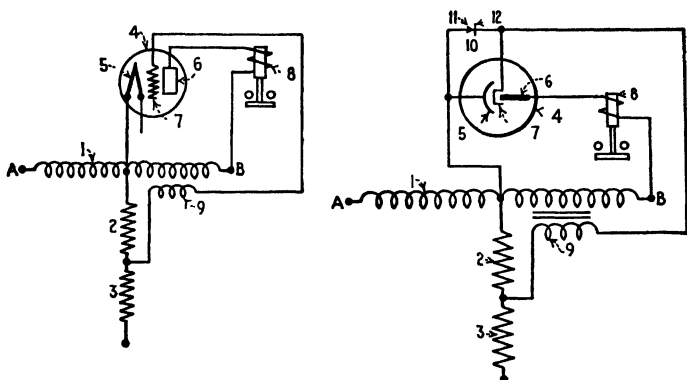
FIG. 87.—Phase-failure relay circuits. Inclusion of rectifier (right) prevents grid from getting wrong firing potential.

that there is one critical phase position of the grid voltage at which a slight shift in phase on one side makes the tube conduct practically the entire half wave, while a slight shift the other way prevents current flow for more than a negligible part of the half cycle. This is best explained by reference to Fig. 88, in which E_p is the voltage applied to anode, E_g that applied to the grid, and E_c is the critical potential below which the grid must be kept to prevent the starting of an arc. The network of Fig. 87 has the property that under normal phase conditions the relation of E_g to E_p is as shown in Fig. 88, which permits conduction during practically the entire positive half cycle; while reverse- or single-phase conditions substantially prevent conduction through the tube. The mechanism of this property of the circuit is explained as follows.

The voltage E_r in Fig. 88 is provided by the IR drop in resistor step 2 of Fig. 87. The voltage E_t is provided by the transformer

winding 9.   These voltages combine vectorially to give E_g, which is shown in Fig. 88 as permitting current to start through the tube near the beginning of the positive half cycle of anode current. The figure shows the voltage conditions resulting from reverse-phase rotation.   It is evident that the phase of E_g has advanced relative to E_p enough to block conduction through the tube except possibly for a negligible period toward the end of the cycle. There are a number of possible single-phase conditions, depending on which of the three lines fails, and on the type of apparatus connected between the various lines, but when analyzed all
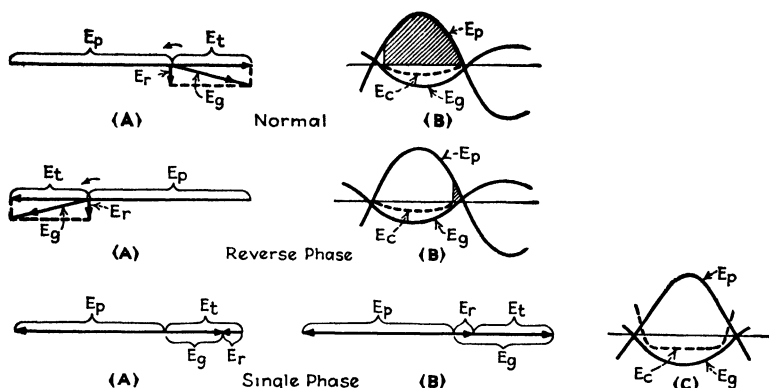
Fig. 88.—Vector diagrams illustrating operation of circuits of Fig. 87.

such conditions reduce to one or the other condition shown in Fig. 88.   The difference lies in whether E_r is in phase with or in opposition to E_p. E_t is always in direct opposition to E_p.   It is only necessary to make E_t large enough to give sufficient negative grid voltage to prevent starting of the tube even when E_t is opposed by E_r.

When an attempt was made to apply Fig. 87 to certain tubes, difficulty was experienced because anode current would start in the tube when the grid voltage exceeded either a definite positive critical value or a definite negative critical value, such critical values being of the same order of magnitude, somewhere between 200 and 400 volts, depending on circumstances.   It was found that when either of these was selected as the critical grid voltage to work with and the phase of the grid manipulated accordingly, it was difficult to so arrange that the grid voltage would not cut either critical line during the positive half cycle under abnormal

conditions. This difficulty was avoided as shown in Fig. 87 by connecting a rectifier between the grid and the cathode so that it was possible for the grid to be made as positive with reference to the cathode as desired without being able to get a high negative bias on the grid on the succeeding half cycle. An alternative was to obtain the opposite result by reversing the rectifier.

Gaseous-tube Press Control.—High-speed presses running above 36,000 I.P.H.[1] require some device to prevent too great an increase in the speed when transferring from the small to the large motor. The customary design calls for about 12,000 I.P.H. on the small motor for threading speed and about 75 per cent reduction on the large motor for take-off speed. If the 75 per cent reduction gives a speed of 9,000 I.P.H. or less, the transfer can be made smoothly and will give a satisfactory take-off. Nine thousand I.P.H. is 75 per cent reduction from 36,000; therefore, above 36,000 some additional equipment is necessary, and it has been the practice in the past to use a fluttering contactor, cutting in and out a step of resistance in the armature circuit under control of a hydraulic relay. A scheme has been perfected which makes use of gas tubes. These are substituted for the hydraulic relay. The fundamental idea on which the operation is based is the matching of the period of oscillation of a circuit containing a condenser, inductance, and resistance.

The secondary frequency of the slip-ring motor varies with the motor speed. In operation the tube control will cause the fluttering contactor to close when the motor is at some definite speed (frequency) and to open at a slightly higher speed. This difference in speed or frequency can be increased or decreased by adjusting one of the rheostats on the panel.

Referring to the line diagram in Fig. 89 the terminals 1 and 2 from which the anode and grid voltages of tube A are driven are connected into the secondary resistor of the main motor so as to give a voltage and frequency varying with the speed of the latter.

The fundamental idea on which operation is based is the matching of the period of the secondary frequency with the definite period of oscillation of a circuit of inductance L, capacity C, and resistance R_2A, etc. E_g has a maximum positive value during the half cycle when E_a is negative. This is accomplished by charging the condenser C through tube B at this time on every

[1] Impressions per hour.

cycle. Due to the rectifying property of tube B, condenser C cannot discharge back through the tube and must therefore discharge through L, R_2A, etc. This discharge will take place in a definite period of time T, depending only on the values of C, L, R_2A, etc., and is independent of the frequency supplied to points 1–2. The actual value of the critical frequency can be
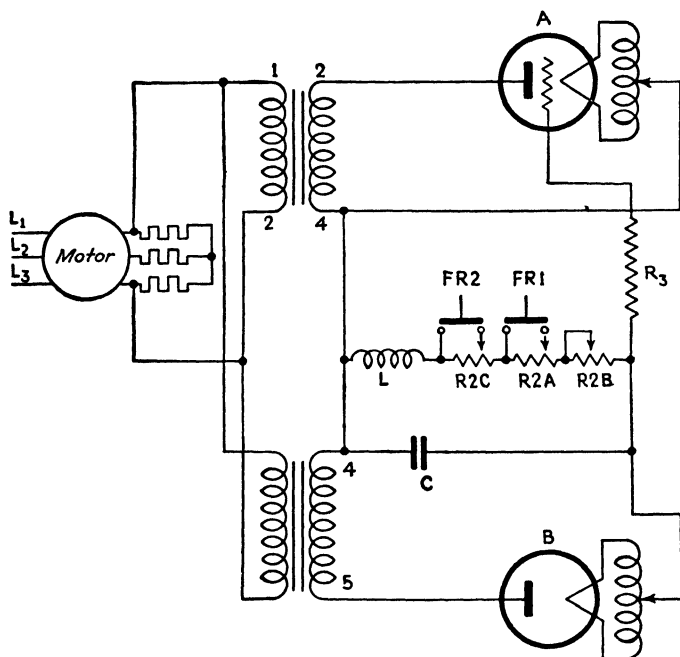
Fig. 89.—Circuit for use in high-speed presses.

adjusted by the rheostat R_2B. Decreased ohms in this rheostat decrease T, thereby increasing the critical frequency.

The purpose of the second rheostat R_2A and the connection through contacts on FR_1 is as follows: In general practice the critical frequency differs somewhat, depending on whether it is approached from a high or a low value, *i.e.*, where it is approached with the tube conducting or nonconducting. Shorting out a part of R_2A through contacts on FR_1 enables the critical frequency under these two conditions to be brought as near together as desired. Tube B is only a rectifier supplying direct current to the grid of tube A. Tube A in this case is a grid-control

mercury-vapor tube. These controllers have been designed by Cutler-Hammer for use on either 60 or 25 cycles.

Application of Controlled Rectifiers to Power Transmission.— The fact that economy of operation and other advantages accrue to the power systems operating from high-voltage direct current instead of alternating current has been mentioned briefly earlier.[1]

With a d.c. system, the amount of power flow from any generator is easily controlled by the voltage of the generator, and this is also true of circuits, and use is made of this feature in d.c. systems. With alternating currents, the amount of power flow can only be controlled by means of the governors of prime movers and change of voltage only results in the amount of circulating current between them.

These characteristics are fundamental and, therefore, it can be said that d.c. systems are much more stable in operation. The operators are in control of the system while with alternating current the system controls the operator.

There is one other fundamental to be noted. All such insulation as cable insulation when subjected to alternating currents suffers from dielectric loss. Corona is ever present, usually intensified by any small void in the insulation. With alternating currents, capacity and inductance produce effects to be contended with. With direct currents, dielectric loss disappears, voids have little, if any effects, corona does not appear except at much higher potentials than with alternating currents.

As power systems grow in size and more stations are connected together, the danger of having too much resistance or reactance in the connections between them is known. But, on the other hand, unless something limits current flow, such as reactance or resistance, the power concentration may be so great that possible destruction to apparatus is great, and what is still more important, the shock to the system may be so great as to cause a shutdown.

If all feeders from an a.c. generating station and all tie feeders were operated with direct current with controlled rectifiers,

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[1] The following material has been taken largely from talks delivered by C. W. Stone, consulting engineer of the General Electric Company, before the American Society of Civil Engineers, New York, Feb. 15, 1933; from the A.I.E.E. paper of C. H. Willis, B. D. Bedford, and F. R. Elder, January, 1935, *Gen. Elec. Rev.*, February, 1935, and May, 1936.

the very nature of these devices is such that the direction and amount of power flow are determined by their connection to the system and are easily controlled by the operator. Large concentrations of power in a fault will not take place and shocks to the system, therefore, become much less.

As the feeders leaving such stations would be direct current and as the tubes connected to the other end of these feeders are used to invert direct to alternating current, the frequency of this alternating current can be made almost anything desired. Thus, power stations of like or unlike frequency can be connected together and can be operated with no fear of loss of synchronizing power and no trouble from hunting.

Now, in cities which have 60-cycle and if necessary 25-cycle current, the only way such systems can be connected together is through motor generator sets. These are expensive, inefficient, and more or less uncontrollable.

Tubes, when used for such ties, are very efficient as the voltage drop in them may be only 25 volts for the mercury-pool type, 14 volts for the hot-cathode type, and as the voltage used for such ties may well be as high as 30,000 volts, the efficiency may be higher than with any other known device.

Such a system as the Chicago Edison Company has many 25-cycle rotary converters for feeding the Edison d.c. network. If the feeders to these rotaries were changed to d.c. feeders and this current were inverted at the substation, the rotaries would operate at their own frequency and the a.c. systems back of them could be either 25 or 60 cycles; and if there were a tendency for them to hunt against each other, the rotaries would not know or care as they would continue to operate at their own frequency, thus greatly increasing the stability of the system.

Another application of tubes would be as ties between the a.c. networks and the d.c. networks. In this case, the tubes would be connected as rectifiers and by a simple automatic control with no moving parts, power would flow from the a.c. network into the d.c. system if it were needed there, as long as the a.c. voltage was maintained high enough, but if it dropped, current flow would stop and in no case could it flow in the reverse direction. In case of a drop on the d.c. network, the current flow from the a.c. network could be limited to any amount desired.

As such installations would be static and nonsynchronous, they would act in many ways like a storage battery always staying on the system and carrying load as long as the a.c. voltage was maintained and picking up their load without attention as soon as the a.c. voltage came back to normal.

While the efficiency of such low-voltage tubes would not be so high as that of large rotary converters in substations, the drop in the d.c. feeders from such substations would be eliminated. Thus, the current at the point where such rectifiers are connected to the system would be obtained at less loss.

Economies of Direct-current Operation.—It has been suggested that tubes be utilized to transmit power through primary cables in cities, and over transmission lines, by making it possible to invert or rectify at the proper ends of the circuit. Cables in cities are operated at voltages of the order of 13,200 volts and are insulated to the ground for the peak voltage generated. They could handle much more power if direct current were transmitted over them.

In the Edison three-wire system each of the three wires of each cable could be connected to a tube rectifier and the other side to ground. Thus all three wires in one cable could have 26,400 volts on them, and three circuits could be built up with an operating potential per circuit of 52,800 volts. The increase of power capacity is obvious.

Furthermore the generators in the power houses could be designed to operate at their most economical frequency; they would be operated at unity power factor. Tubes would replace high-voltage oil switches. Reactance and capacity effects would not affect the transmission of d.c. power.

Objections to the Transmission of Power at High Direct-current Voltages.—Engineers, however, are quick to point out that all of the characteristics of d.c. transmission are not favorable. On d.c. systems there is greater possibility of an insulator flashover—therefore voltages lower than the full peak voltage of the a.c. circuit may be required.

The savings to be effected by d.c. systems depend upon the cost of the terminal equipment, its life, and its service charges.

A system of constant-current d.c. transmission has been developed by C. H. Willis, B. D. Bedford, and F. R. Elder at the General Electric laboratories employing rectifiers to convert

alternating current to direct current for transmission and grid-controlled rectifiers for inverting the direct current back to alternating current for utilization. C. W. Stone, A. W. Hull, and E. F. W. Alexanderson of that company have also contributed to this important phase of electronics.

The following description is taken from a report of their disclosures at the Winter Convention of the A.I.E.E. 1935. More recent work is described in the *General Electric Review* of May 1936.

Direct-current power transmission by constant current is in itself not new, but the work described represents the first time that such transmission has been accomplished in a commercial capacity, even in test, by means of electronic tubes.

In brief, the essential features of the new system of electric power transmission are:

It is a constant-current direct-current system.

It is a system where the power flow is in one direction only at the will of the operator; but the power can be transmitted in either direction if desired.

The amount of power flow is under the control of the operator at all times.

No wattless power is transmitted.

A short circuit on any circuit of this type results in a reduction of power flow on the circuit involved.

Power can be transmitted by either overhead or underground lines any distance desired.

A circuit of this type can be tapped at any point to furnish power or to take power.

The nature of the circuit is such that systems of like or unlike frequencies can be operated together to feed any other system of like or unlike frequencies.

Overhead systems of this type should be more reliable, and less disturbance will be caused by lightning.

The system cannot become out of phase or out of synchronism with the system feeding it or with the system receiving power.

As most loads of power systems are of lagging power factor, the transmission of the resulting wattless current adversely affects the capacity of the circuits, the transformers, and the generators feeding the system. With the new system, all the load on the generating stations will be slightly leading, rather than lagging; and no wattless power is transmitted. The wattless current required by the loads is supplied by the inverter equipment. This results in lower generator and transformer heating and improved regulation.

In the paper presented by Willis, Bedford, and Elder there was described a circuit arranged for the transmission of 150 kw. of power, the circuit operating at a maximum peak of 15,000 volts and 10 amp. An even larger installation, in which connection is made to a 13,800-volt, 60-cycle, three-phase, a.c. bus of the New York Power and Light Corporation with a circuit for transmitting a constant direct current of 200 amp. at 15,000 volts

A B C

Disconnect switch
Oil circuit breaker
Monocyclic network
3-phase A-C. constant current

3-phase full wave rectifier

D-C. reactor

Constant current D-C. line

D-C. Reactor

3-phase full wave inverter

3-phase A-C. constant current
Monocyclic network
Oil circuit breaker
Disconnect switch

A B C   *3-phase A-C.constant voltage power system*
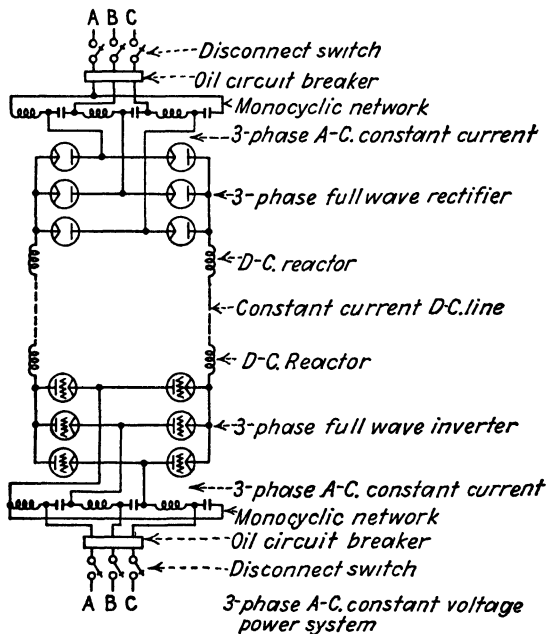
Fɪɢ. 90.—System for taking power at alternating current, transmitting it at high-voltage direct current and then using it as alternating current.

is described in the May, 1936, *General Electric Review.* This circuit includes about 15,000 ft. of underground conductor and is connected back to the 13,800-volt bus, after being inverted from direct to alternating current of the proper characteristics.

In this 3,000-kw., constant-current, d.c. circuit a group of condensers and reactors is so connected to the 13,800-volt bus that constant-current alternating current is obtained; the circuit being tuned so that this current is 200 amp., the voltage varies with the load. The alternating current is then rectified by means of six two-element tubes. (If two-way transmission is desired, controlled rectifiers are used.)

High-voltage, constant-current direct current is thus produced. After passing through some smoothing reactors the current goes through the 15,000-ft. length of underground conductor—representing transmission of the energy—after which it is received and passed through another d.c. smoothing reactor. Six inverter tubes then change the direct current into 60-cycle, three-phase alternating current of constant value. Another group of reactors and condensers then change this constant current into constant-potential alternating current, the current output at this point varying with the load. Connection is then made back to the a.c. bus in the factory. Such an arrangement of condensers and reactors constitutes what is known as a *monocyclic* network.

One feature of such a network is that, if it is tuned for a certain definite current, and if it receives this current, constant potential results at the output terminals. On the other hand, if it is supplied from a constant-potential bus, constant current will be obtained at the terminals. Neglecting the losses in the reactors and condensers, the power factor on the two sides of the network is equal but of opposite value.

No transformers have been used in the installation, but, in a commercial installation, it is probable that transformers would be used at the sending end for increasing the voltage to that point desired and at the receiving end for reducing the voltage.

The rectifier end of this network connected to a constant-potential system will furnish a sufficient voltage to cause the full-load current of the d.c. system to flow. If a short circuit of low resistance exists close to the rectifier, the voltage furnished by the rectifier will be very low—only sufficient to overcome the low resistance of the short circuit. The power flow, then, will be reduced; and, if the resistance is of very low value, the voltage will collapse to practically zero.

At the receiving end the tubes, being arranged to pass current in one direction only, will operate as an inverter as long as constant current is received from the rectifier. Failing to receive this constant current, the inverter becomes a rectifier and draws full-load current at low voltage from the a.c. system to which it is connected. The polarity of this current will be reversed, however.

If a short circuit occurs on the d.c. line, and if the constant current of the system is 200 amp., and the regulation of the line

is 10 per cent, then the current flow into the short circuit will be about 20 amp. The voltage on the d.c. line drops to that point necessary to cause 20 amp. to flow in the short circuit.

As soon as the short circuit is removed, normal current flows in the normal direction, the rectifier furnishes its share of the current, the inverter receives the current, and the current is inverted and furnished to the receiver system as constant-potential alternating current.

If, when the line is operating under normal conditions, the cable is short-circuited by means of a single-pole knife-blade switch, the voltmeter reading drops practically to zero but the current remains constant. If the switch is then opened, the voltage returns very promptly and at all times the current remains constant.

If the line is short-circuited through a 6-amp. 250-volt cartridge fuse, the fuse blows, thus opening the short circuit but little disturbance is caused by the blowing of such a small fuse.

In still another demonstration an insulator normally used on an 11,000-volt a.c. line is employed. Two such insulators are usually used on such a line, but in the demonstration there is only one. If an attempt is made to arc over the insulator by short-circuiting it with a small wire, the arc-over of the insulator cannot continue. It is indicated that overhead lines can be built with fewer insulators than are now required for a.c. power, since, while they may arc over because of a lightning flash, the dynamic current of the system is limited, and the arc will extinguish itself. Each insulator thus becomes a lightning arrester to clear the line of any high-voltage transients.

Temperature Control.—Systems of temperature control will be found in the chapters on amplification and light-sensitive devices. Grid-controlled rectifiers may be used in place of relays in controlling the flow of current into the heating coils of a bath, as shown in Fig. 91. This system used at the Electrical Testing Laboratories shows a way of using a 2.5-amp. 1,000-volt grid-controlled rectifier to control a 10-amp. 120-volt a.c. circuit.

This arrangement in connection with a toluol thermostat has satisfactorily controlled the air temperature in a large test box to within 0.01°C. It has no mechanical parts to wear or stick and has operated continuously for long periods without measureable deviation from the set temperature. It has been used in the

close control of baths for accurate resistance measurement of materials having relatively large temperature coefficients.
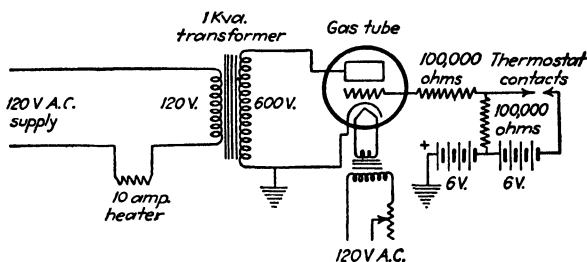
FIG. 91.—Use of tube, controlled by thermostat, to control bath temperature.

A somewhat more complex circuit[1] is shown in Fig. 92 and used in a medium temperature furnace in a resistor plant where the requirements as to allowable temperature variation are quite severe.

A special resistance thermometer is placed in the furnace and made the fourth arm in an a.c. bridge.   By variation of one of the
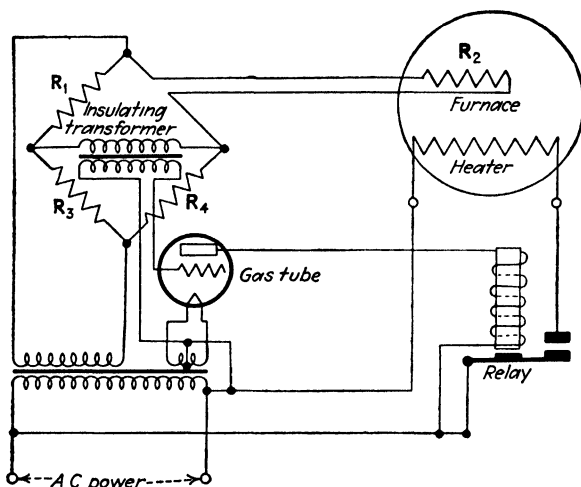
FIG. 92.—Bridge circuit for temperature control.

fixed arms of the bridge the temperature may be adjusted.   No voltage is present across the bridge at correct temperature.   An

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[1] PODOLSKY, LEON, *Electronics*, July, 1933.   See also HIBBEN, JAMᵀˢ H., *Rev. Sci. Instruments*, May, 1930, p. 285; and NOYES, BRADFORD, *J. ('ical Soc. Am.*, vol. 17, p. 128, 1928.

increase or decrease in temperature unbalances the bridge, applies a voltage to the insulating transformer, is amplified and applied to the grid of a controlled rectifier. An increase in temperature causes the grid bias on the tube to increase and stop the flow of current on the half cycle when the anode is normally conducting, *i.e.*, the positive half cycle. A decrease in temperature permits the tube to conduct and to close the power relay. One furnace of this type permitted a temperature to be maintained without difficulty at 500°C. to within 5°.
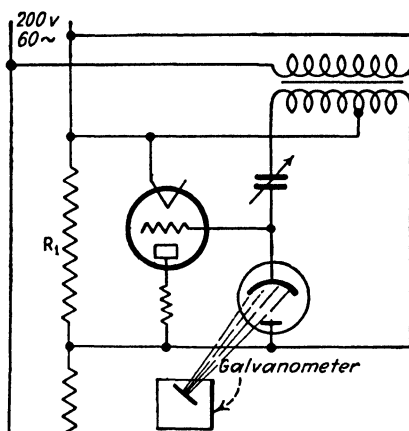
Fɪɢ. 93.—Combination of phototube and gas triode for temperature control.

Another temperature-control system[1] using gaseous triodes is shown in Fig. 93 used in the growth of single crystals of alkali halides. It was necessary to keep temperature constant at some times and, at others, to vary it as slowly as 2°C. per day. The circuit has the advantage that it has no mechanical relays, and produces continuous modulation reducing the tendency of the furnace temperature to hunt or oscillate.

The thermocouple is constantan-chromel, one junction in the furnace and the other in an ice bath. The galvanometer has a sensitivity of 40 megohms, resistance 80 ohms. More or less light falling on the photo-electric cell through a V-shaped slot varies proportionately the flow of current through the tubes by the phase-variation method.

[1] ZABEL, R. M., and R. R. HANCOX, Use of Thyratron for Temperature Control, *Rev. Sci. Instruments*, January, 1934.

The tube has a capacity of 5 amp., and since 18 amp. were required, a large proportion of the heating current flowed through R_1, the tube passing about 3 amp.

At a furnace temperature of 880°C., the maximum variation from the normal temperature was 0.06°C.

In radio transmitters designed by Kishpaugh and Coram[1] of the Bell Telephone Laboratories, the quartz crystal used to maintain the transmitter on its proper frequency is kept at a constant
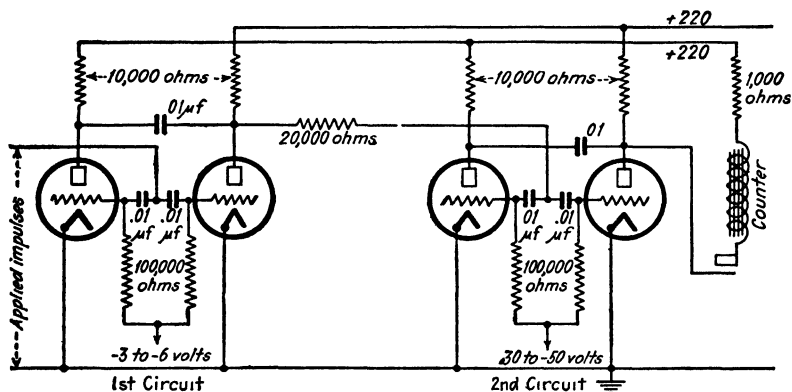
Fig. 94.—Circuit which will count 1,250 impulses per second.

or nearly constant temperature by means of a thermostat which permits a grid-controlled rectifier to pass current when the contacts are open. When the correct operating temperature is reached, the contacts close and make the grid of the tube continually out of phase with the plate so that no heating current is passed. Thus a relay is eliminated; the thermostat need handle but small currents.

High-speed Automatic Counting.—A useful circuit developed by C. E. Wynn-Williams[2] allows of recording or counting the passage of 1,250 objects per second (over 4 million per hour). The principle of the method employed is that of arranging several units of two grid-controlled rectifiers in cascade to reduce the rate of counting by a factor of 2 per unit, until the final counting rate is sufficiently slow for a mechanical meter. In each unit

[1] Low-power Transmitters, *Proc. Inst. Radio Eng.*, February, 1933.

[2] *Proc. Roy. Soc.*, London, May, 1932. See also WYNN-WILLIAMS, C. E., *Proc. Roy. Soc.*, A132, 295–310, 1931. HULL, A. W., *Phys.*, vol. 2, No. 6, June, 1932.

the steady bias potential applied to both grids by the bias battery through the grid resistances is slightly more negative than the critical potential required to prevent arcs from striking. Suppose that by some means an arc has been started in one tube; the firing of the other tube consequent upon the arrival of an impulse at the grids results in a sudden drop of its anode potential, and the resulting negative potential surge, transmitted through a condenser to the anode of the other tube causes the arc in that tube to be extinguished. Each tube responds to one-half the
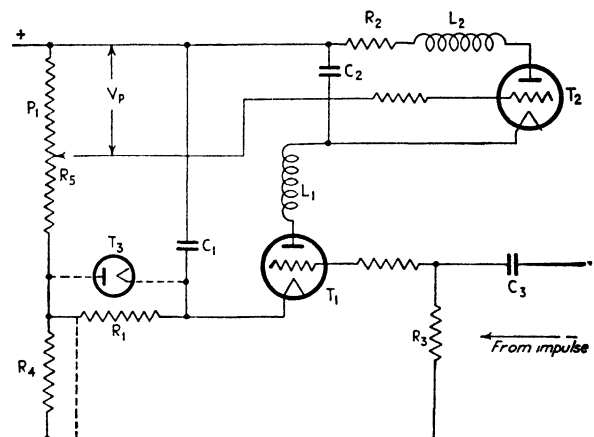
Fig. 95.—Circuit in which T_2 fires after T_1 has accumulated a desired number of impulses.

total number of applied impulses. Only one of the tubes in each stage is coupled to the preceding unit of two by connecting the input side of the grid condensers to the anodes of one of the tubes through high resistances.

This scheme employs the parallel-type inverter. For each pair of tubes used, a counting ratio is secured. Thus six tubes are required to give a rate of 8.

Still other high-speed counting circuits have been devised. For example, the single-tube inverter[1] has been utilized in counting impulses up to 7,200 per minute or as low as two per minute. A single circuit is shown in Fig. 95 and its method of operation involving a multiplier tube follows.

With no impulses being received capacitor C_1 is charged through resistor R_1 to the voltage drop across potentiometer

[1] LORD and LIVINGSTON, *Electronics*, September, 1933.

P_1, tube T_1 is held nonconducting by the negative voltage across resistor R_4 applied through resistor R_3. Capacitor C_2, which is several times the capacity of C_1, will be assumed for the moment to have zero charge. Now let an impulse voltage be impressed across R_3 of sufficient magnitude and duration to fire T_1. Capacitor C_1 will then discharge through T_1 and inductor L_1 until the voltage across C_1 is less than the voltage to which C_2 has been charged. This difference of potential between C_1 and C_2 is brought about by the decay of the magnetic flux of L_1, built up by the flow of current through the windings during the early part of the discharge period, inducing an e.m.f. in the windings of L_1 in such a direction as to maintain the current flowing in the circuit for a time even though the voltage of C_1 is less than that of C_2. Capacitor C_1 is charged again through R_1 but, since the potential of C_1 was less than that of C_2 for a time, the anode of T_1 was negative with respect to the cathode and for a sufficient length of time to allow the grid, which is again negative, to regain control. This cycle of operation is repeated until the charge received by C_2 causes the voltage across it to exceed the algebraic sum of the voltage V_p across potentiometer P_1 and the critical grid voltage of T_2, then T_2 will fire and discharge C_2 through R_2 and L_2.

To state the conditions for the firing of T_2 algebraically let V_g = critical grid voltage of T_2 (negative if the critical grid voltage is negative), let V_c = voltage of C_2, and let V_p be the voltage determined by the setting of the slider of potentiometer P_1. Then T_2 will fire when $V_c = V_p + V_g$. When T_2 conducts C_2 discharges through T_2, L_2, and R_2, the relation between C_2, R_2, and L_2 being such that C_2 is completely discharged before the next impulse is received by the counter circuit. The discharge of C_2 returns the condition of the circuit to that existing at the start.

From the preceding description of the operation it may be seen that tube T_2 will fire once for every definite number of times tube T_1 is fired by the received impulse, the ratio being controlled by changing the setting of potentiometer P_1. If the operating coil of a counter is substituted for inductor L_2 the counter will operate each time C_2 discharges through T_2.

At high speeds the circuit of Fig. 95 changes speed, the ratio increasing because C_1 discharges tube C_2 before C_1 is fully charged,

thereby requiring more applications of T_1 before C_2 is charged sufficiently to fire T_2. Inclusion of the mercury-vapor rectifier T_3,—shown in dotted lines—(and the change of the connection of R_1 to below R_4) stops the charging of C_1 when it reaches a potential negative enough to cause T_3 to conduct.

A circuit for operating a conventional counter is shown in Fig. 96. Discharge of a capacitor in the circuit of L_2 induces a voltage in the secondary that fires the tube which conducts until the relay
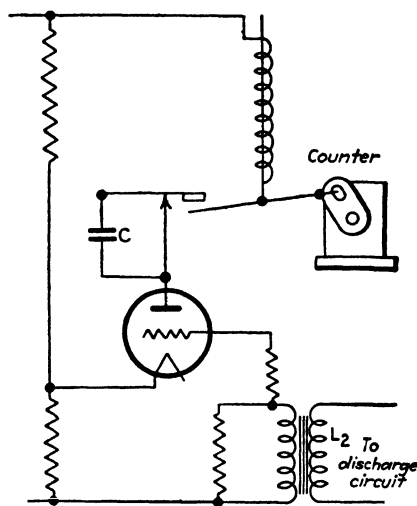
Fig. 96.—Counter using gas triode.

or counter armature opens the anode circuit and permits the grid to regain control.

Impulses for Counters.—The phototube and amplifier will follow high-speed motion of objects to be counted, provided they move rapidly enough to cut the beam of light rapidly so that a steep wave front is produced which can be properly amplified and pass through a resistance-capacity network of the thyratron. A regenerative d.c. amplifier[1] shown in Fig. 97 will solve this problem. Here are shown two amplifiers (high-vacuum triodes) and a phototube.

When the phototube is illuminated, the impedance of this tube is low, resulting in a low negative or perhaps positive bias on T_2. The consequent low impedance puts a high negative bias on T_1

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[1] LORD and LIVINGSTON, *loc. cit.*

from the current flowing through R_1.   Little current flows in the anode circuit of this tube and little output current results.

Now if the phototube slowly be cut off from the light, its impedance increases and the grid of T_2 will be negatively biased.
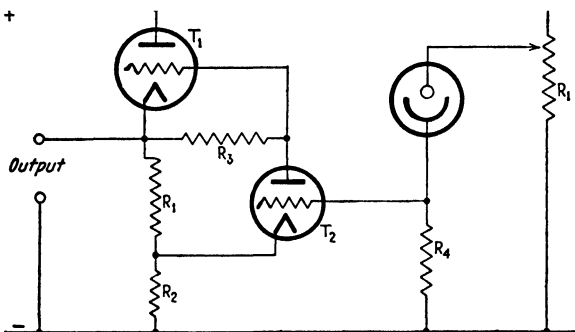
Fig. 97.—Phototube controlled d.c. amplifier for providing counting impulses.

Therefore, T_1 will draw more current through R_2 which will increase the negative bias on T_2 which, still further increased by the bias from the phototube circuit, causes a regenerative action.

By proper adjustment the anode current of T_1 increases slowly up to some critical value and then very rapidly increases.   Now if the light is turned on, the reverse action takes place, the current decreasing slowly and then very rapidly.

Another source of impulses might be a small voltage induced in a coil by a piece of iron carried by part of the mechanism in a cyclic operation.   A pair of make-and-break contacts could be utilized.

Voltage Impulses for Control.[1]— In Fig. 98 is shown a method of control whereby the phase of the grid voltage is changed by varying a d.c. bias.   The basic idea is that of electrostatic energy storage in the grid circuit, by means of an oxide rectifier. These voltage variations are brought about by charging a capaci-
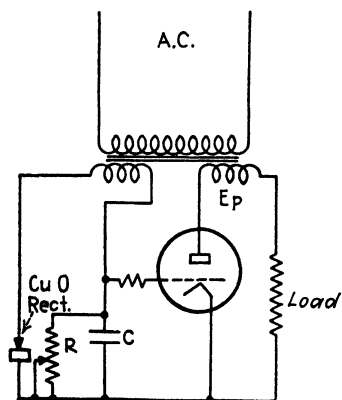
Fig. 98.—Control of phase by grid bias.

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[1] Thyratron Grid Control, *Gen. Elec. Rev.*, June, 1934, p. 290.

tor through a rectifying circuit and then allowing it to discharge freely through a circuit containing a variable resistance. The capacitor loses this charge in a definite time through R. Throughout most of this discharge period, which is adjustable, the grid is sufficiently negative to prevent conduction in the tube. The circuit, therefore, provides a rectifier having a wide range of control and extreme ease of adjustment. This circuit is very sensitive to changes in the critical grid voltage.
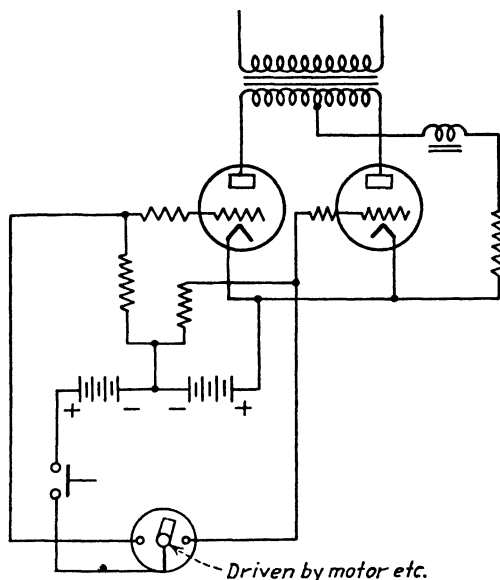
Fig. 99.—Mechanical interrupter for producing control voltage peaks.

Methods usually described for grid voltage use either a d.c. voltage or a sine-wave voltage for grid control. For many applications this is the simplest and most desirable method. Some problems can be attacked more successfully by applying what might be termed an impulse voltage to the grid. Figure 99 represents a method of using an impulse voltage to control the average output voltage of a rectifier and to provide a means whereby network short circuits and arc-backs can be readily extinguished by grid-controlled rectifiers. The voltage regulation is carried out in such a way that the grids are continuously connected to a negative voltage, and a positive-peak voltage is applied to the grids during a brief instant for the purpose of

ignition. Thus the average d.c. voltage can be varied by changing the phase position at which the positive peaks occur, *viz.*, by moving the mechanical commutator relative to the brush, which is driven synchronously by the a.c. supply. At the instant that an overload occurs, the positive supply line to the grids is interrupted by means of a high-speed relay, whereby the ignition of further anodes is prevented. The anode which is conducting at that time continues until the current passes through zero, at which instant the short-circuit current is interrupted.
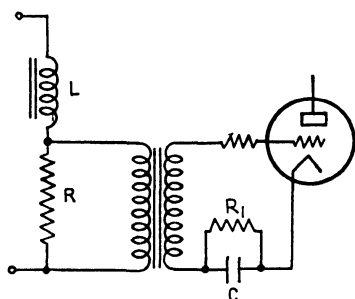
FIG. 100.—Saturable reactor for producing control voltage peaks.

Although Fig. 99 shows a mechanical commutator having contacts and moving parts for producing impulse voltage peaks, static electrical devices also may be arranged to provide the same excitation. A circuit consisting of a reactor and a resistor connected in series for producing voltage impulses is shown in Fig. 100. The reactor saturates near the zero of the applied voltage wave, and the resulting current peak produces a voltage drop across the resistor R. This voltage impulse is transmitted by transformer action to the grid circuit where it is superimposed upon a negative bias. The phase angle of the terminal voltage of the grid circuit can be changed with respect to the anode voltage by phase-rotating devices.

FIG. 101.—Glow tube for impulse excitation.
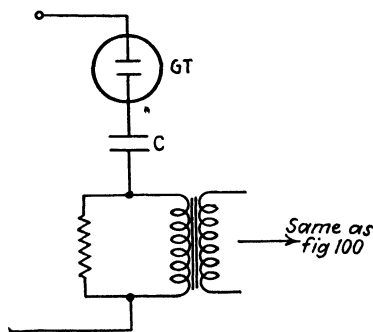
The valve action of a glow tube connected in series with a condenser and resistance is sometimes utilized. The glow tube (Fig. 101) does not ignite until the voltage exceeds the starting voltage, after which it continues to conduct until the supply voltage drops below the extinguishing voltage. When the glow tube breaks down, a surge of current flows through the capacitor, decreasing along an exponential curve. The corresponding voltage drop across the

resistor is transmitted to the grid circuit in the same manner as described above.   While such a circuit provides accurate starting, rapid ionization, and some positive-ion bombardment, it depends for its accuracy on the breakdown voltage of the glow tube.

Figure 102 is a typical grid circuit in which an impulse transformer is employed.   By using an E-type punching in the construction of the transformer, two grids 180 deg. out of phase may be excited from the secondary windings.   During the positive half cycle, current flows in the grid-cathode circuit, charging the capacitor C.   Resistance R_g leaks part of the charge
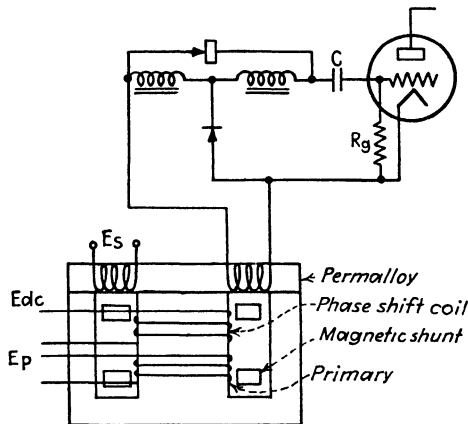
Fig. 102.—Magnetic structure of transformer to deliver peaked wave for control purposes.

from C, so that when there is no positive-ion current, the capacitor will not become charged to the peak value of the transformer voltage.   If R_g is made of Thyrite, the resistance of which increases with decreasing voltage, most of the leakage from the capacitor will occur near the maximum voltage.

At a lower voltage, the capacitor C will retain enough of its charge to maintain control even though the grid excitation fails for several cycles.   The negative peak of the transformer is shunted by the copper oxide rectifier connected in series with a reactor.   Because the current in this element opposes the building up of flux in the associated core, all of the flux change will take place in the adjacent permalloy core.   This doubles the rate of voltage rise in the active winding.

The permalloy section saturates very quickly when a certain flux density is reached, and the flux then passes through the

magnetic shunts. The flux thus changes rapidly from the positive saturated condition to the negative saturated condition, producing a peaked voltage of very narrow width. During the saturated period, there is no change in flux in the secondary core; consequently, the secondary voltage must be zero during that period. Since the maximum secondary voltage occurs when the flux is passing through zero, the voltage of the secondary winding will be a peaked voltage of short duration. The rate of change from a high voltage to a low voltage is dependent on the shape of the saturation curve of the permalloy and the permeance of the joints. The magnetic shunts which carry the flux during the saturated condition may be adjusted to give any value of exciting current.

Fig. 103.—Ion clean-up for parallel inverter.

Impulses for Rapid De-ionization.—In Fig. 103 is shown one arrangement of a circuit for rapid de-ionization as applied to the parallel inverter. The power circuit consists of the load transformer, the commutating capacitor, the line reactor, and tubes. The grid circuit contains the usual circuit elements: the grid transformer and grid resistors R_1 and R_2 with the addition of the impulse voltage element; the oxide rectifiers and the small condensers C_1 and C_2. The function of the circuit containing the rectifier and C_1 is to apply to the grid an impulse derived from the voltage existing across the commutating capacitor at current transfer. Thus, when one tube is conducting, the commutating capacitor is charging according to the polarity indicated on the diagram. When the capacitor becomes fully charged, and the grid voltage reverses, the other tube is made conducting, thereby forcing the anode of the first tube negative with respect to its cathode by the voltage on the commutating capacitor. At this point, the condenser, the second tube, C_1, and the first rectifier come into play, since the inverse voltage is applied in such direction that the impedance of the grid transformer enables the voltage of the capacitor to become available for cleaning up the residual ions through a low-impedance circuit.

CHAPTER V

LIGHT-SENSITIVE TUBES

The electron tubes described in the previous chapter have heat as their immediate source of energy—a cathode is heated by passing an electric current through it; electrons are emitted from this cathode when the proper temperature is attained.

Another large class of electron tubes secures its initial energy in another way—by radiating the cathode with a beam of light, visible or invisible. The cathode thus illuminated emits electrons. In both types of tube the electrons, after escaping from the cathode, are directed toward a positively charged plate, and upon arrival there give up a quantity of electricity. The summation of the arrival of these carriers per second of time constitutes an electric current measurable in amperes or fractions of amperes. On the way to this positive plate the electrons may be retarded or accelerated by additional metallic electrodes sealed into the envelope containing the cathode and anode. Thus the thermionic tube may have several additional electrodes placed within the structure to modulate or in some manner control the flow of current from cathode to anode via the electrons.

Light-sensitive tubes have been constructed with more than two electrodes but they have not come into general use. There are several types of light-sensitive tube as indicated below. The terminology used in dealing with this group of electron tube is exceedingly loose. In popular language the light-sensitive tube is an "electric eye," but it is far from that. It will be seen later that the photocell seldom sees as the eyes see—that is, it has a different spectral response and, of course, differs radically in other ways. All the three widely used types of tube are called indiscriminately "photocells," "photo-electric cells," or "phototubes." The oldest term is photo-electric cell; the newest phototube. In addition there are several trade names which are coming into general use.

Value of the Light-sensitive Tube.—From a practical viewpoint the light-sensitive tube provides the industrial engineer with another element or medium of control, a new degree of freedom. Other electron tubes secure their impulse largely from variable electrical quantities; the phototube enables an engineer to use a beam of light and places at his disposal the vast science of optics. Thus the phototube adds one more fundamental property of nature, that of light, to the repertoire of the control engineer. The microphone and amplifier make it possible to use sound for purposes other than communication; the phototube makes it possible to employ light for purposes other than illumination. The beam of light now controlling many processes, most of them very simple, many of them complex, requires no space and when not required is simply put out of the way by turning off the illumination; it is instantaneous in its action having no inertia, is inexpensive to maintain, and has two degrees of control—magnitude and wave length.

Types of Light-sensitive Tubes.—The general types of electron tubes utilizing a beam of light to produce electrical energy are as follows:

1. *Photo-emissive*, in which a beam of light causes a surface to emit electrons. An analogy is the thermionic tube in which a heated cathode emits electrons. In the latter case heat energy is converted into electrical energy (at very low efficiency); in the former case light energy is converted into electrical energy (also at very low efficiency). These electrons are attracted toward a plate maintained at a positive potential by an external battery; this electron-carried electric current is amplified (usually) by means of thermionic tubes which, in turn, control relays or perform other useful functions involving power.

Fig. 1.—Typical phototube.

2. *Photo-conductive,* in which the resistance of a material to the flow of current is materially altered when it is illuminated by a beam of light. Selenium is the best-known example of this type of light-sensitive material. An analogy is a conductor whose electrical resistance varies with temperature.

3. *Photo-voltaic,* in which a passage of electrons from one material surface to another is accelerated by illuminating the surface with light. These devices act as rectifiers, the electrons passing more readily from one plate or surface to the other than they do in the opposite direction. The voltage developed by these surfaces is independent of the area illuminated; but the power output varies as the area. The analogue is a wet or dry cell or chemical battery in which current flows from one electrode to another and in which the terminal voltage is independent of the area of the active material.

If the emissive type of phototube seems to occupy more space here it is only because it is older and solely for this reason in wider practical use, and because more has been published about its characteristics and its accomplishments. Undoubtedly many of the applications made of the emissive type of tube could be performed by the other types as well, and in the future they will probably do so.

Photo-electricity.—The light-sensitive cell is not new; indeed it is about 40 years old which is really an ancient device scientifically speaking. The fact that certain surfaces emitted electrons when illuminated with ultra-violet light has been known since the time of Hertz, 1887, but the most rapid development of the photocell into a rugged, uniform, long-lived product has taken place within the last five years. Scientists used the emissive-type photocell for many years, deploring its bad qualities, such as its fatigue, but until a large market was found for it the disadvantages overcame its good characteristics for general use.

This market was the sound-motion-picture industry requiring an annual production of approximately 100,000 photocells, and needing them in full-fledged finished condition almost overnight. For this purpose the cells must be uniform, have long lives, and be rugged enough to be shipped and handled like the amplifier tube. Today there are cells of many kinds, some sensitive in the

ultra-violet, some in the red, some having a characteristic very much like that of the human eye.

The photocell, of the emissive type, however, is not by itself able to do much. The currents taken from it are so feeble—millionths of amperes—that usually they must be amplified before being put to use. Although cells have increased in sensitivity so that they are ten times better than those of five years ago the maximum current is only a matter of about 60 μa when it receives one lumen of light, which is about what an average cell gets from a 50-watt lamp at a distance of 6 in.

The meagerness of the photocurrents is due to the small amount of energy that is absorbed by the light-sensitive surface from the beam of light. A cathode of a thermionic tube may be heated by several watts of energy, much more than is absorbed by the phototube cathode. Thus the former emits electrons to the extent of milliamperes or even amperes while the latter emits only microamperes. Even if the currents obtainable from a photocell are so small, it is of tremendous importance. It is a light valve of incredible speed and remarkable accuracy. By means of intermediate apparatus it will control vast quantities of power, although the actual energy derived from the beam of light directed on it may be infinitely small.

The laws of photo-electric emission were pronounced by Einstein in 1905 and have proved to be of vast importance to physicists in setting up modern atomic and quantum theories.[1]

These laws state simply that (1) the number of electrons emitted from a cathode surface depends exactly and linearly upon the intensity of light falling on that cathode; and (2) the velocity of the electrons thus emitted depends only upon the surface of the cathode and the wave length of the light but not upon its intensity or any other factor. This phenomenon can be explained only by the quantum theory; in fact the photo-electric effect forms one of the foundations of this vastly important theory.

Fundamentals of the Photo-emissive Tube.—A phototube of the emissive type consists essentially of two elements in an exhausted container in which there may, or may not, be an inert gas at a low pressure. The cathode has the property of emitting

[1] On the fundamental laws of photo-electricity, see HUGHES, A. L., *Elec. Eng.*, August, 1934, p. 1149.

electrons under the action of light. The most common materials used for this purpose are the alkali metals.

A potential of 15 to 25 volts on the anode is sufficient to attract all the electrons that are emitted; an increase of anode voltage above this value will cause little or no increase in current in the high-vacuum tube. When a low pressure of an inert gas is
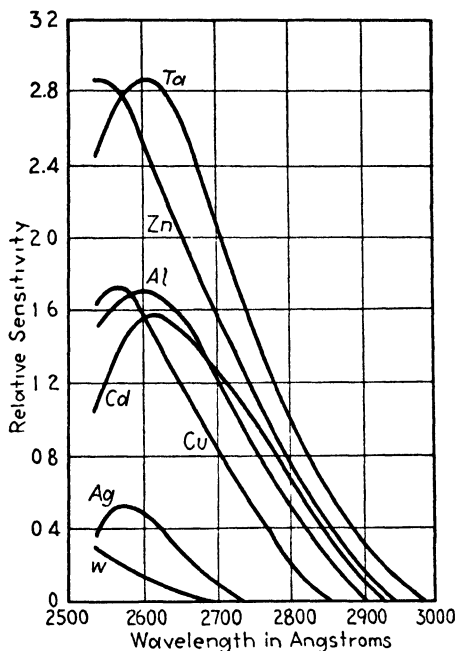
Fig. 2.—Change in threshold frequency for various cathodes. (*After Rentschler, Henry, and Smith, Rev. Sci. Instruments, December*, 1932.)

present, however, the original current is increased by the ionization of this gas by as much as ten times. The amount of ionization increases rapidly as the anode voltage is increased until a point is reached at which the discharge breaks into a *glow discharge*. Since this glow discharge will destroy the tube it is always necessary to limit the anode voltage to well below this value and to use a series resistance for additional protection.

Phototubes, therefore, are classified as *vacuum* or *gas-filled*. In general, the vacuum types are the most stable in their characteristics and give an output directly proportional to the light flux incident on the cathode. The gas-filled tubes have the

advantage of greater output per unit light flux due to the ionization of the gas.

The color sensitivity of phototubes is quite different from that of the human eye and varies widely with the type of light-sensitive surface.   Certain tubes are designed for operation in the ultraviolet region, while others are suitable for operation only in the visible or infra-red region.   When it is necessary to have a device with a definite color sensitivity, a standard tube is often used with a light filter[1] having the proper transmission characteristic.

Much has been accomplished within the past few years in developing cells whose maximum of response falls in particular regions of the spectrum.   The figures show the effect of utilizing one or the other of various light-sensitive surfaces.   According to the "International Critical Tables," vol. 6, p. 68, the following table shows the wave lengths for maximum sensitivity for various elements:

Element	Wave Length for Maximum Sensitivity in 10^{-8} cm.
Lithium	2,800
Sodium	3,400
Potassium	4,400
Caesium	4,800

Often combinations of two or more elements are utilized; and many complicated processes have been worked out for sensitizing a photocell after construction.   These matters will be found discussed in various books and scientific publications.   The cathode material may be one of several compounds usually of the alkali metals such as caesium, potassium, lithium, etc.   These compounds are coated on any one of several metals, silver, for example, or on the walls of the glass container or envelope.   The anode may be of any metal or shape or size so long as it does not shut off the light.   Because phototubes are used industrially and in photometry with incandescent lamps whose energy is largely toward the red end of the spectrum, considerable research has been directed toward making cells more sensitive in the red. For many purposes it is desirable to have the response of the cell

[1] See KOLLER, L. R., Use of Filter with Photoelectric Tubes, *Rev. Sci. Instruments*, March, 1931.

approximate that of the human eye and by means of filters it can be made to do so.

For any given spectral color, a vacuum cell delivers a current directly proportional to the intensity of the light between at least 0.1 and 10,000 foot-candles.

Gas versus Vacuum Cells.—The vacuum cell has a linear relation between current and light intensity; the gaseous cell does not have this linear relation. For general control uses the
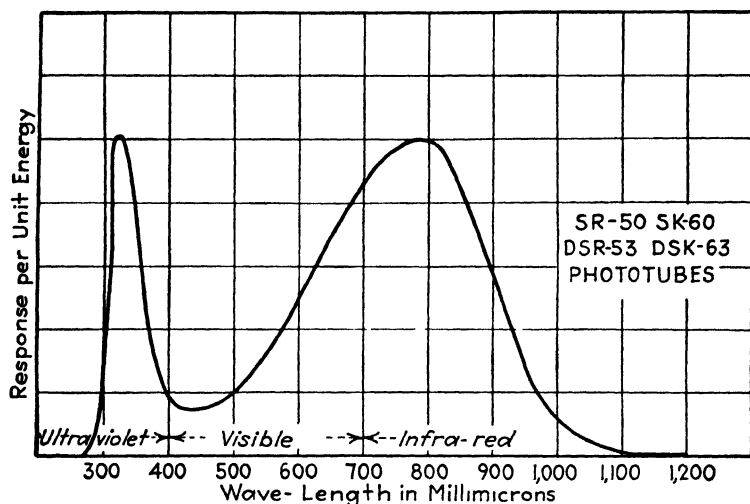
FIG. 3.—Spectral sensitivity of typical phototube.

gaseous cell is frequently used because of its greater sensitivity; for purposes of measuring light intensities the vacuum cells are employed because of linearity. The range of surfaces now found useful in phototubes is fairly large, the exact nature of the surface depending upon many factors, *e.g.*, the spectral composition of the light with which it is to be used, the desired sensitivity, the life in comparison to its cost, uniformity, etc.

The gaseous cells usually use argon. The gas must be inert so that it does not react with the sensitive surface and it must not "clean up." In the latter process positive ions acquire sufficient speed under the action of the electric field in the tube to be permanently driven into the walls of the tube and thus the gas pressure is decreased by a decrease in the number of gas molecules. Neon and helium are used in some cells. The gas pressure may be from 20 to 150 microns.

The amplification due to ionization may be considerable; in practice a ratio of ten is about as high as is consistent with stability. If the voltage between anode and cathode is raised to a certain point, the current flowing through the tube continues even if the light is removed. Manufacturers of phototubes give directions for their use which will avoid any danger of this glow discharge occurring.

Characteristics of Photocells of the Emissive Type.—In the belief that engineers are more interested in the applications of phototubes than in the chemistry of their sensitive surfaces, or
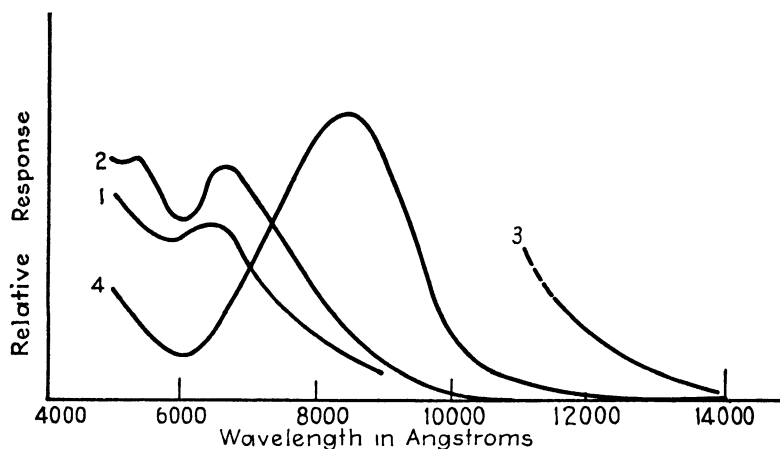
FIG. 4.—Spectral curves for experimental caesium oxide phototubes showing extent of excursion into infra-red. (*After Tives.*)

in the history leading to the present highly advanced state of the art, tube construction, etc., has not been treated here to any extent. These data may be gathered from several excellent books mentioned in the bibliography at the end of the chapter.

Within wide limits the current from vacuum-type emissive-type cells is linear with respect to the intensity of the illumination. This fact makes them valuable for measurement purposes or for communication, as in sound-motion pictures, where variations in light are translated into variations in sound.

With a fixed voltage between cathode and anode, then, the current varies directly as the illumination. With a given illumination the current increases with increasing voltage between cathode and anode. Thus the vacuum cell differs but little from

a two-element thermionic tube, the illumination corresponding to the temperature of the filament.

Phototube Ratings.—The following definitions of the ratings applying to photocells are generally accepted. When illuminated
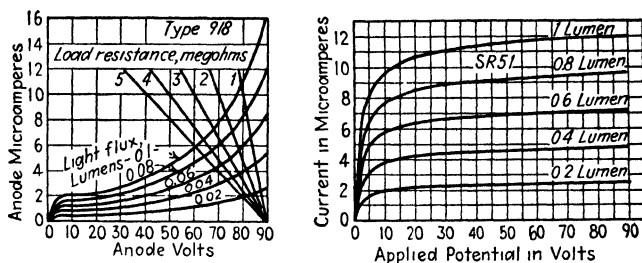
FIG. 5.—Characteristics of typical photo-emissive cells.

by modulated light, various new terms and ratings appear resembling those in use with respect to amplifier tubes. Inasmuch as industrial engineers will seldom if ever be called upon to use circuits in which the light is modulated, these definitions are not given here.[1]
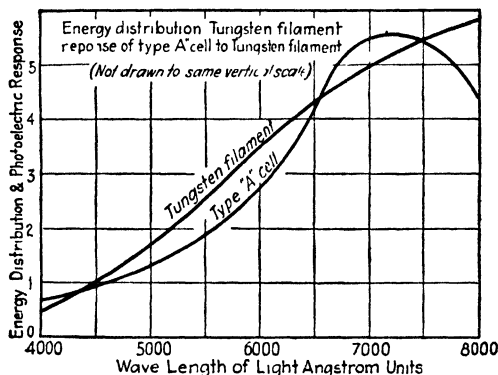
FIG. 6.—Response of cell sensitized to be most sensitive in red.

Maximum anode current is the maximum instantaneous value of current that should be allowed to pass through the tube.

Maximum anode voltage is the maximum instantaneous value of voltage that should be impressed on the tube.

[1] METCALF, C. F., *Proc. Inst. Radio Eng.*, vol. 17, No. 11, November, 1929.

Gas amplification ratio is the ratio of the current when ionization exists to the current due to primary electrons alone.

Sensitivity is expressed as the current in microamperes per lumen of light flux. It is generally measured at a light intensity of 0.1 or 0.5 lumen. The temperature of the lamp acting as the source of illumination is of great importance in making a sensitivity measurement, small changes in lamp temperature making large changes in the current output of the phototube. A temperature of 2870°K. has been tentatively agreed upon
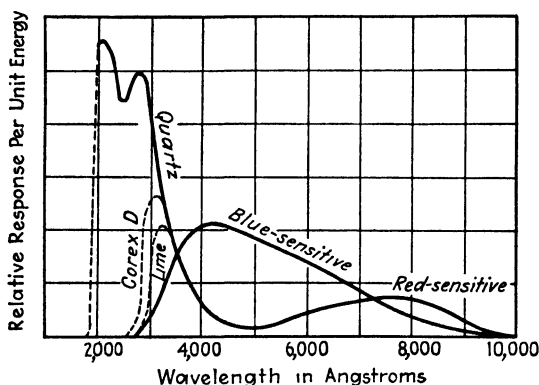
Fig. 7.—Spectral curves, caesium oxide cathodes. Note effect of envelope material on the red-sensitive type.

Typical Phototubes.—There are many photocells on the market. Those whose characteristics are given here are quite representative of American practice. The color sensitivity of a tube designed to give high-current output when illuminated with ultra-violet light is shown in Fig. 7. It has practically no response at wave lengths longer than 4,000 angstroms. The bulb is of quartz and the active surface is sodium deposited on the inside wall of the glass container. It is vacuum in type; the output is practically unchanged for anode voltages above 25 volts. With 67.5 volts the sensitivity is about 12 μa per lumen when located 25 in. from a quartz BY Uviarc burner operating at 320 watts and 68 to 70 volts.

In Fig. 8 are the color characteristics of a highly sensitive vacuum-type cell developed late in 1933. It is very small, the sensitive surface and anode being placed in an automobile headlight bulb of 1⁷⁄₁₆ by 2⅜ in. maximum dimensions. The tube has

a sensitivity of about 35 μa per lumen which is the sensitivity of a good gaseous cell. It has the stability of a vacuum cell. It has an unusual infra-red sensitivity. It responds to the heat from a body that is not even glowing in the dark (a wave length of about 12,000 angstroms, or a temperature of 500°C. or 900°F.). With an automobile headlight lamp as the source of illumination (2600°C. or 4700°F.) the tube gave a 5 or 6 per cent response through a heat-transmitting filter; usual phototubes have a response of about 0.5 per cent under these conditions.
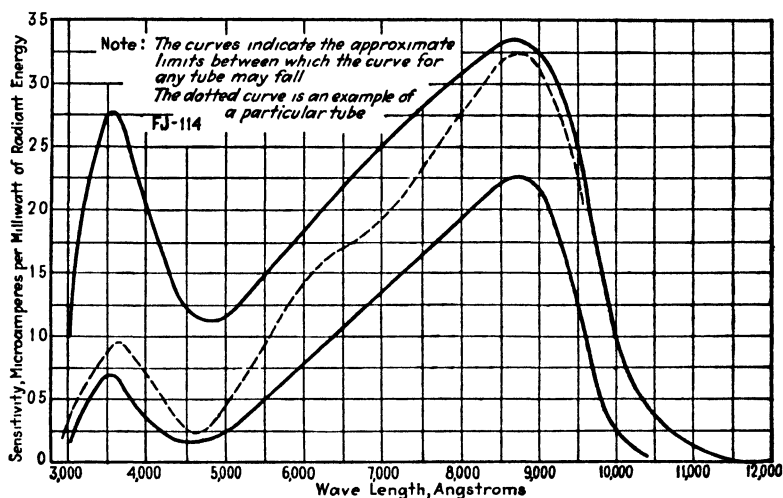
Fig. 8.—Tube developed in 1933 of small size and high sensitivity.

An interesting detail of construction of the new tube is the method of joining the caesiated silver coating of the bulb (the cathode) to the contact in the base. A piece of 3-mil spring material fastened to the contact post presses a piece of platinum foil, $\frac{1}{2}$ mil thick and welded to the tip of the spring, so that it is held against the glass bulb. This platinum foil is fused to the glass, which has the same coefficient of expansion, by the tip of a flame applied to the outside of the bulb. Then, when the bulb has been coated with its mirror-like, light-sensitive, caesiated silver film, the connection is complete.

Tubes of this new type were used in the Harvard and Yerkes observatories when light from the star Arcturus was used in opening A Century of Progress Exposition at Chicago.

The response of a typical gas cell is shown in Fig. 9. This tube is argon-filled, has its maximum sensitivity in the red, another smaller peak of sensitivity in the blue. Its sensitivity is 50 μa per lumen when illuminated by a Mazda projector lamp
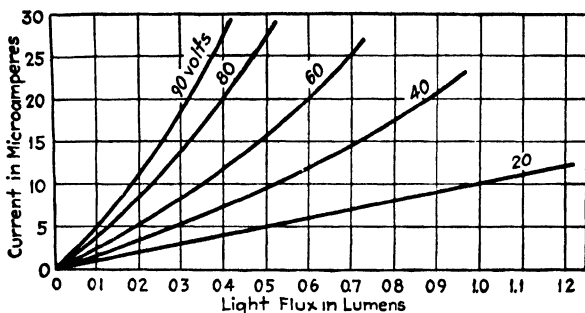
FIG. 9.—Gas cell characteristics.

operated at a temperature of 2870°K. The light was admitted to the cathode through a circular aperture $1\frac{1}{2}$ in. in diameter whose center was located $2^{11}\!/_{16}$ in. above the bottom of the shoulder of the base prongs. A current reading was taken for a light flux of 0.1 lumen with an applied potential of 90 volts across the tube and with a series resistance of 1 megohm.

Measurements of Photocell Currents.—Although the currents from light-sensitive surfaces may be measured by sensitive galvanometers, the use of tube amplifiers is desirable. If the photocell current is made to pass through a known resistance, the voltage drop along this resistance can easily be measured by means of a vacuum-tube voltmeter. Thus in Fig. 10 the plate current through the meter is balanced out by means of an accessory battery. Then if the phototube is illuminated current will flow through it and impress a voltage across the grid resistance of the tube. This voltage will make the grid bias less negative and permit current to flow through the plate circuit meter. This
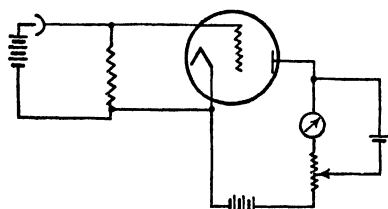
FIG. 10.—Circuit for measuring phototube currents.

meter may be calibrated in terms of the voltage appearing across the grid resistor.

A useful type of d.c. amplifier[1] is the push-pull circuit shown in Fig. 11. This may also be considered as a Wheatstone bridge of which the two grid circuits comprise two arms and the two plate circuits the other two. As long as there is no current flowing in the phototube circuit, the two plate currents will be equal and consequently the two points a and b will be at the same potential, and a meter connected between these points will read zero. Any current flowing through the phototube circuit will disturb this balance and give a meter deflection. The advantages of this circuit are its high sensitivity, the proportionality
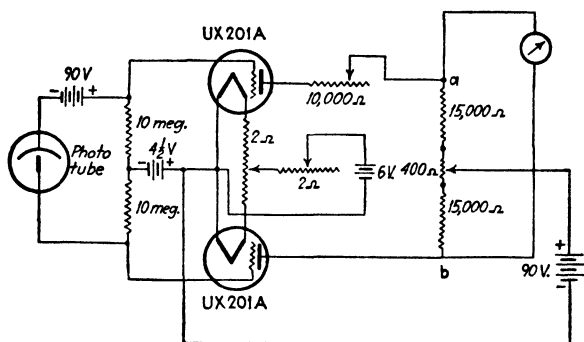
FIG. 11.—Direct-current amplifier for measuring light-sensitive cell currents.

between input and output over a wide range, and the fact that it is not affected by changes in battery voltage.

Measurement by Modulating the Light Beam.—Since it is much simpler and more satisfactory to amplify a.c. voltages than d.c., the light entering a phototube may be modulated before measurement. This modulation can be obtained by interrupting the light beam by means of a toothed wheel, a sector disk, or merely a disk with holes around the periphery and rotated upon the shaft of a motor. The holes, or teeth, etc., may be shaped so that the wave form of the a.c. generated in the cell is anything desired.

In color and other measurements this method of securing high amplification is frequently utilized. For example, the task of comparing the color of red bulbs might be undertaken. To sort theatrical bulbs of this color by the eye becomes not only a tedious

[1] KOLLER, L. R., *J. Western Soc. Eng.*, vol. 36, No. 1, February, 1931. See also EGLIN, J. M., *J. Optical Soc.*, May, 1929.

but an inaccurate task because of the lack of sensitivity of the eye to this color, and because the eye soon fatigues and loses the power of discrimination.

The bulbs may be screwed into a socket one after the other and conveyed in front of an aperture behind which is a rotating wheel with holes near its edge as shown in Fig. 12. The currents generated in the phototube are amplified (if necessary) and rectified in the second tube of the vacuum-tube voltmeter. The rectified currents are read by the operator on a milliammeter. Cells
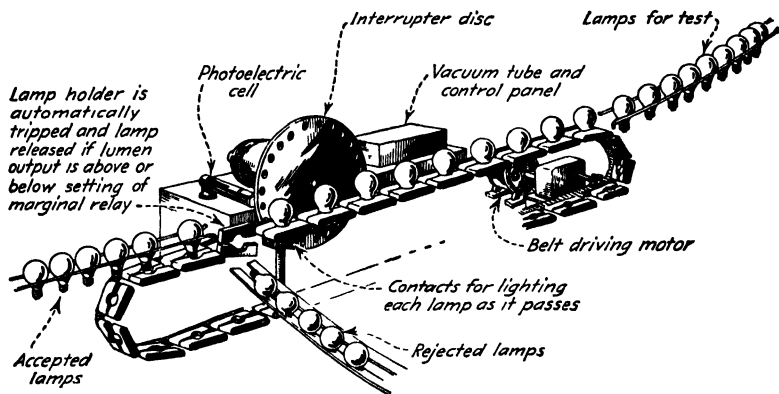
Fig. 12.—Apparatus for testing red theatrical bulbs. (*E. B. Kirk.*)

which are too dark or too light may be rejected. This requires that the lamps have the same color, *i.e.*, from the same batch. The rectified current meter may be replaced by an automatic rejection device which will throw a relay when tubes are to be rejected or accepted.

Combination of Photocell and Amplifier.—The grids of many tubes are light-sensitive.[1] For example, if the grid of a 45 is left floating, *i.e.*, is not connected to anything, it will assume a negative charge and a certain plate current will flow. Now if the grid is illuminated, the plate current will change.

The features of a tube used in this manner are as follows: (1) its output reponse is in direct proportion to the log of the light intensity values impressed on it, (2) with 50 foot-candles it is possible to operate a cheap relay directly in the plate circuit of the tube without further amplification, (3) it takes very little voltage to operate it, (4) due to its log relation characteristic, it

[1] KOECHEL, W. P., *Electronics*, p. 372, December, 1932.

can be made to give a direct reading on one meter scale, of a ratio range of light intensity of 1:1,000 or greater if desired.

The grid of the tube if left floating assumes a charge of approximately 1 volt negative. The exact value depends on the tube construction, and other element potentials.[1] With from 4 to 20 volts on the plate of a 45, this charge will be slightly over 1 volt.

This 1 volt acts as a bias, just as though a bias voltage were actually applied to the grid. Therefore, if the plate voltage
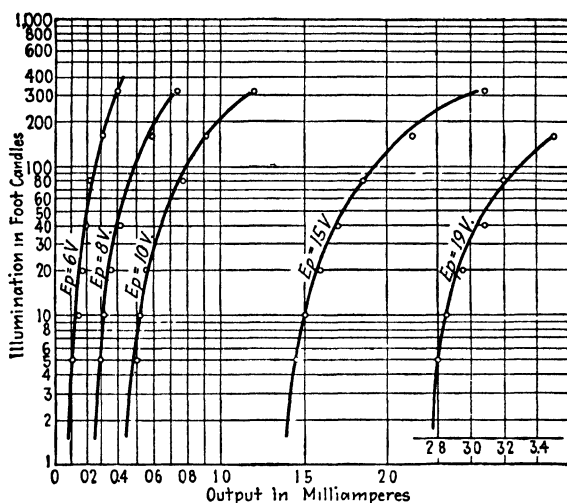
Fig. 13.—Curves of amplifier triode acting as light-sensitive tube.

is adjusted almost to cut-off, with 1-volt bias, the same plate-current reading will be obtained with the grid floating provided no light is shining on the tube. If the grid is illuminated the plate-current reading will change. The relation of plate-current change to light intensity is surprisingly consistent.

The apparent action of light is to make the grid emit electrons faster than it can accumulate them due to being in a free state or floating. Therefore, it is extremely important that the grid be well insulated.

It is possible to use the tube "as is" for various applications, where it is not necessary to detect small changes in light. When used for operating a relay, the tube is connected as shown in Fig. 14. This relay should be capable of operating on from 1 to 10 ma.

[1] See MORECROFT, "Principles of Radio Communication," 1st ed., p. 487.

The plate voltage will, of course, have to be high enough to give the required I_p for operating the relay, with the required light shining on the tube.
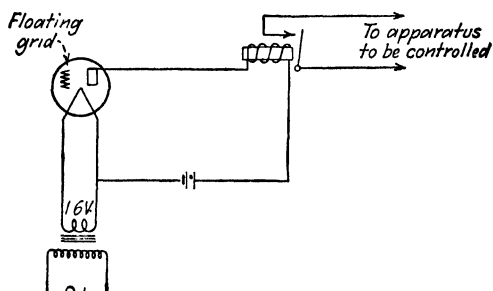
Fig. 14.—Control of relay by light-responsive high-vacuum triode.

For example: A Western Electric type B-40 relay (400 ohms) can be adjusted to operate on 1.5 ma. Therefore, if 15 volts plate supply is used, the plate current will be about 1.4 ma. with the tube dark. If now a source of 50 foot-candles or higher illumination is caused to fall on the grid of the tube, the plate
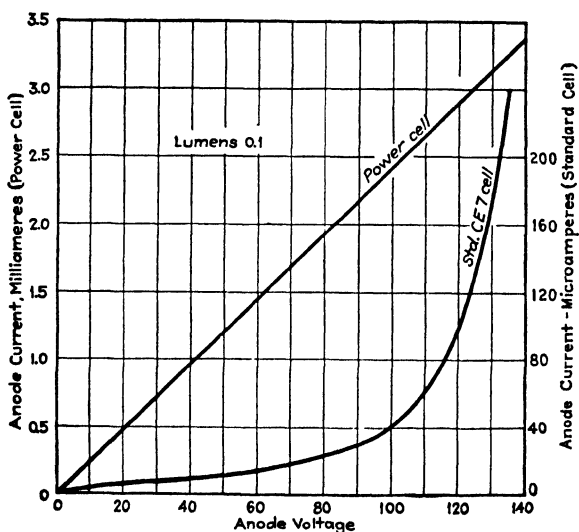
Fig. 15.—Linear response of combined phototube-amplifier tube.

current will rise to 1.7 ma., and operate the relay. The same end can be accomplished by using a higher plate voltage, if a less sensitive relay is used.

Light-actuated Amplifiers.—A combination[1] of a light-sensitive cathode and a triode in the same envelope gives much more consistent results than the tubes just described. The output from such a combination of light-sensitive and a thermionic tube is shown in Fig. 15.

Several similar tubes have been described[2] and there are various methods of making thermionic tubes light-sensitive.

The Photo-glow Tube.—D. D. Knowles has developed a gaseous cold-cathode tube which becomes conducting when
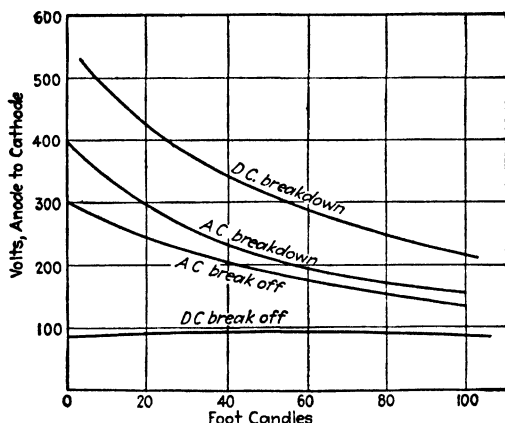
Fig. 16.—Characteristics of Photo-glow tube.

illuminated. The voltage between cathode (light-sensitive) and anode is so adjusted that it is slightly below the value required for breakdown. Then upon illumination the electrons emitted from the cathode lower the voltage required for break-down. As in the grid-controlled rectifier, the current to the anode is independent of the control (in this case the illumination) once the discharge has begun. Therefore when operated on direct current, the only way to stop the current is to cut off the anode voltage or by lowering it almost to cut-off. On alternating current, the current stops at the end of the cycle, which makes the anode positive with respect to the cathode.

[1] Made by H. A. McIllvaine, Continental Electric Company.

[2] ZWORYKIN and WILSON, "Photocells and Their Application," 2nd ed., pp. 217–222. See also ASADA and HAGITA, *J. Inst. Elec. Eng. of Japan*, vol. 51, No. 1, p. 8, 1931; No. 2, p. 17, 1931.

The tube (DSK-62) will carry 5 ma., sufficient to operate a sturdy relay. It is suggested for service where only occasional breakdown is encountered, for example, as a protective device operating when a flash-over of a commutator on a d.c. generator occurs. The breakdown characteristics of a typical tube of this type are shown in Fig. 16 (after Zworykin and Wilson).

General Characteristics of Emissive-type Light-sensitive Tubes.—These tubes are high-resistance devices delivering weak currents. Therefore they must be worked into circuits, or loads, of high resistance and high insulation. Great care must be taken that the feeble currents produced by the meager emission of electrons from the cathode under stimulation of illumination are not lost before their work is performed.

For this reason it is usual practice to operate the amplifier tube, which acts as intermediary between the phototube and the relay, as near, physically, as possible to the light-sensitive tube. On circuits operating from alternating current it is particularly important that short well-insulated leads be used. With a properly insulated connection between phototube and amplifier a distance of 10 to 25 ft. may intervene between them. This connecting wire had best be insulated and shielded to prevent not only leakage but the interference to the circuit from stray fields in the vicinity of the circuit.

A high-impedance circuit is prone to pick up undesirable noise and other interference. Since the phototube-to-amplifier connection is of very high impedance, the lead wires should be properly protected.

Photo-conductive Tubes.[1]—Tubes of this type exhibit radically different characteristics from the emissive type of light-sensitive tube. In this case a substance, selenium being the most prominent example, has a high resistance to the flow of electric currents. But when this substance is illuminated this resistance decreases permitting more current to flow. The differential between the "dark" current and the "light" current is the useful change in current that operates relays or does other work.

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[1] An excellent treatment of photo-conductive and photo-voltaic types of light-sensitive tubes will be found in Hughes and DuBridge, "Photoelectric Phenomena." See also, Nix, Foster C., Photoconductivity, *Rev. Mod. Phys.*, vol. 4, pp. 723–766, October, 1932.

The ratio between the dark and light resistance may be as much as 10 to 25 times. In general the ratio is not so great as this, high-ratio tubes seemingly tending to be unstable.

Selenium Tubes.—Selenium, an element discovered by Berzelius in 1817, has the peculiar property of changing its resistance to the flow of current when illuminated by light. Thus a selenium tube belongs to the group of devices known as "light-sensitive." This peculiar property of selenium was discovered
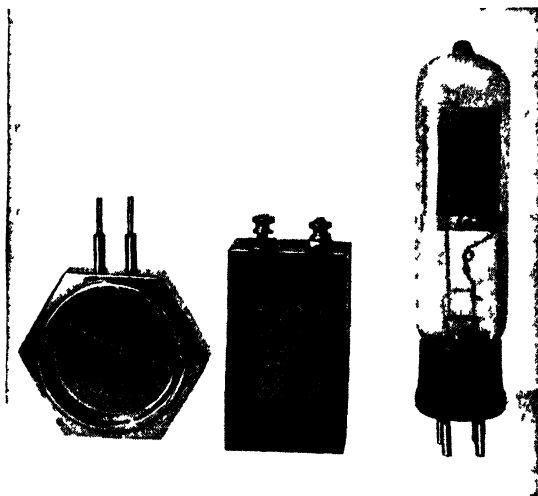
Fig. 17.—Typical selenium and voltaic cells. (*Courtesy of Samuel Wein.*)

by Willoughby Smith, in 1872, who was using rods of this element as resistors. When illuminated by daylight or artificial light, the resistance varied appreciably. The resistance under the best of illumination is high but the *difference* of resistance between its condition in the dark and under illumination is sufficient to make the element both interesting and valuable.

Early efforts to make selenium cells, or bridges as they were called, were not very successful. The cells suffered from aging, were slow in response, were affected by temperature, and did not deliver the same current change under the same change in illumination at various times. Modern technique involves not only placing the selenium element in a vacuum tube and then evacuating it, but some cells are manufactured by a process by which the selenium layer is formed in vacuum.

Such cells are usually made by painting a thin layer of selenium over two parallel conductors insulated, except for the selenium, from each other. When the tube surface is illuminated, the resistance between conductors decreases and more current flows from a battery through a load, usually a relay. For example, two enameled covered wires may be wound side by side on a glass sheet or other insulated plate. Then the enamel is scraped off one surface and the selenium painted on. After undergoing a heat-treating process, the cell is ready for operation.
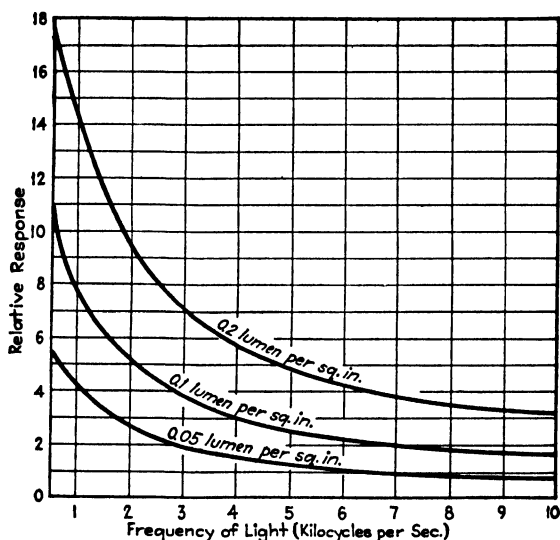
Fig. 18.—Selenium-tube (FJ-31) frequency characteristic.

Because of temperature effects, dark-current variations, and changes of sensitivity, selenium cells have not come into general use.

The FJ-31 Selenium Tube.—A good example of the adaptation of modern vacuum-tube technique to the long-known property of selenium is the FJ-31 tube (General Electric). The selenium surface is formed entirely in vacuum by a process similar to that used in vaporizing metals in thin films on the bulbs of radio receiving tubes in manufacture. A dry inert gas is admitted during the annealing process.

By this method of manufacture the difficulties due to instability experienced in the past art have been largely overcome. Insta-

bility was discovered to be due to the effects of moisture and oxygen in the air during the formation and annealing of the selenium layer as well as during operation of the tube. Forming the surface in vacuum eliminates this difficulty. Tubes made in
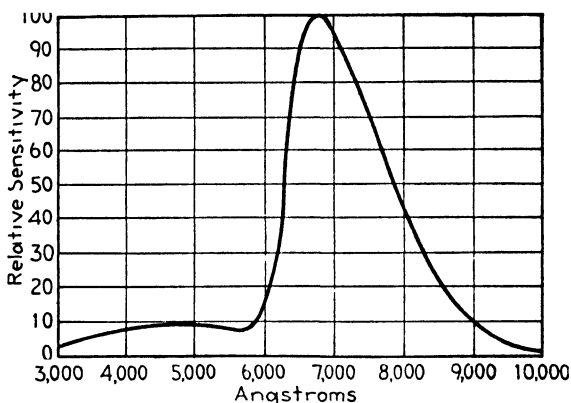
FIG. 19.—Color response of FJ-31.

this way show relatively small temperature changes and remain practically constant in characteristic over a long period of time.
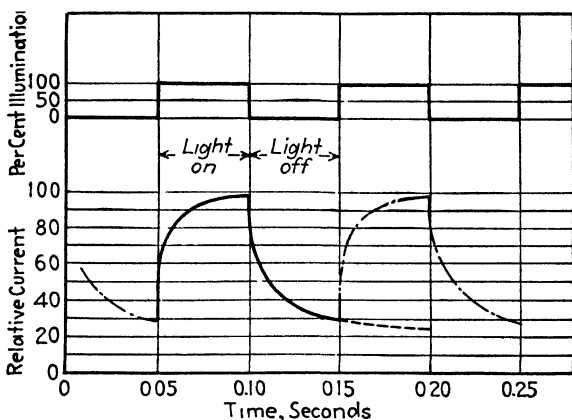
FIG. 20.—Speed of response of selenium tube.

In the FJ-31 a very thin layer of material is employed and therefore the time lag is reduced from that in tubes made according to the older methods. The dark resistance is of the order of 6 megohms. When illuminated, this resistance may fall as low as 0.75 megohm giving a resistance (and hence a current) change

of 8 to 1.   On the curve in Fig. 20 it will be noted that 90 per cent of the total change in current takes place in one-hundredth of a second.

The Burgess Radiovisor Bridge.—Another selenium tube, originally developed in England, but changed somewhat for the American market is the Burgess Radiovisor Bridge.   The base consists of a thin glass sheet upon the face of which a gold grid
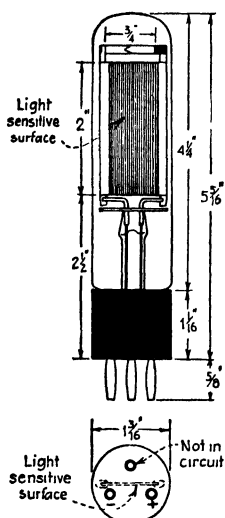
FIG. 21.—Burgess selenium bridge.
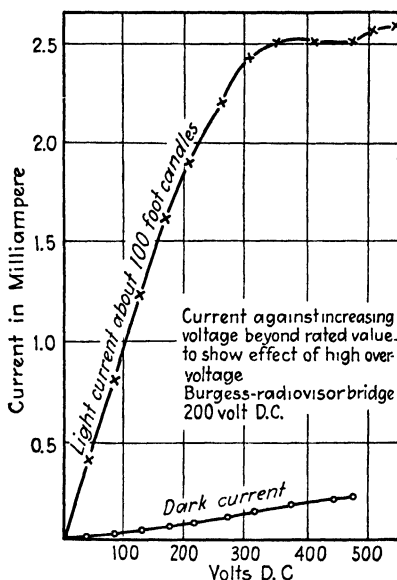
FIG. 22.—Characteristic of Burgess Radiovisor selenium tube.

is fused by a special ceramic process so that the grid is in intimate and permanent union with the glass.   The grid is in the form of interlocking combs, and over it is spread the molten selenium. By a thermal treatment it is converted to crystalline selenium of considerable sensitivity to light.   The gold layer is so thin that the capacity effect is small, the selenium layer is of the order of 2.5×10^{-3} cm. thick permitting the most to be made of any exposure to light.   The distance between grids mentioned above as well as the thickness and width of the selenium can be varied in manufacture so that the dark resistance can be varied from about 0.1 to 30 megohms.   The standard bridge has a dark resistance of about 4 megohms and will show a current change of

from 100 to 150 μa upon illumination. The bridge can be made in forms which will operate from 12 to 800 volts and with current capacities of from 1 to 250 ma.
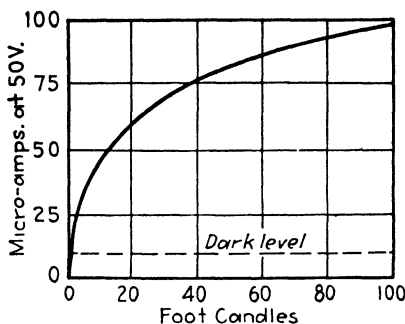
FIG. 23.—Output of Acoustolite cell.

Photo-voltaic Cells.—Another type of light-sensitive cell has come into extensive use within the past few years. This makes use of the Becquerel effect by which an e.m.f. is created in an electrolyte or an electrode when the electrolyte or electrode is illuminated. This e.m.f. may be used to drive current through a load of any sort. In some cases sufficient power is obtained to operate a sensitive relay without any amplification.
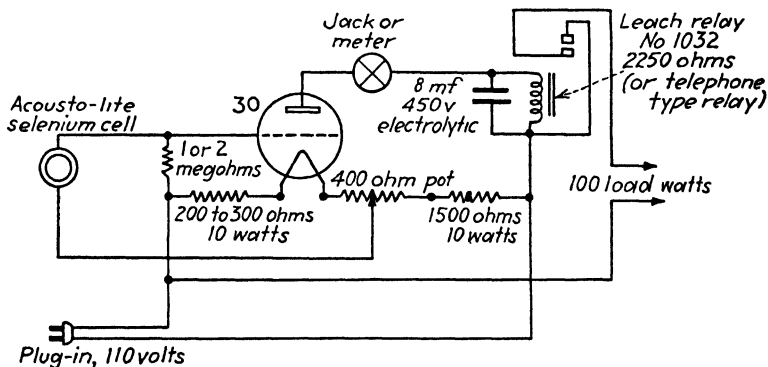
FIG. 24.—Complete circuit recommended for Acoustolite selenium cell.

A typical cell described in 1930[1] had a sensitivity of 150 μa per lumen. The current-illumination characteristic was linear between 0 and 100 lumens per square foot. The maximum

[1] FINK and ALPERN, Photo-voltaic cells, *Am. Electrochem. Soc.*, Detroit, Sept. 26, 1930.

response was obtained at a color of about 4,600 angstroms. When equipped with a quartz window and exposed to direct
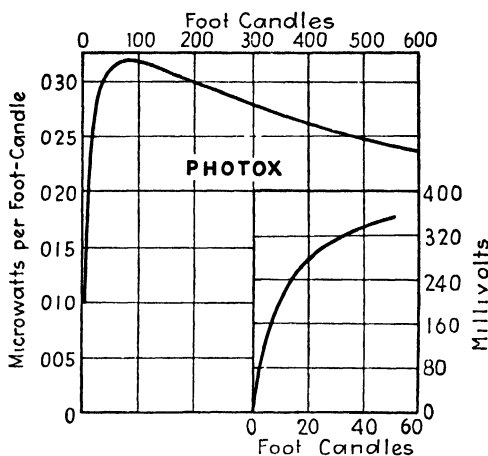
Fig. 25.—Characteristics of Westinghouse Photox unit.

sunlight, a current of 15 ma. was obtained. During such overload the current decreased slowly but the cell recuperated when left on open circuit. The recuperation period was from several hours to a full day depending upon condition of overload.
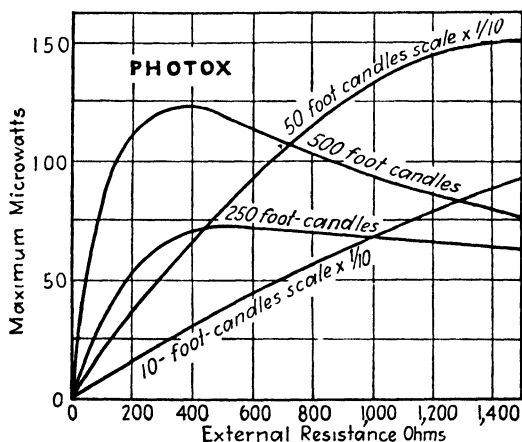
Fig. 26.—Characteristics of Westinghouse copper oxide cell.

Dry-disk Photo-voltaic Cells.—A type of cell which seems to have particular promise is that in which two dissimilar elements

or compounds are in contact and in which electrons are enabled to pass more easily in one direction than in the other.
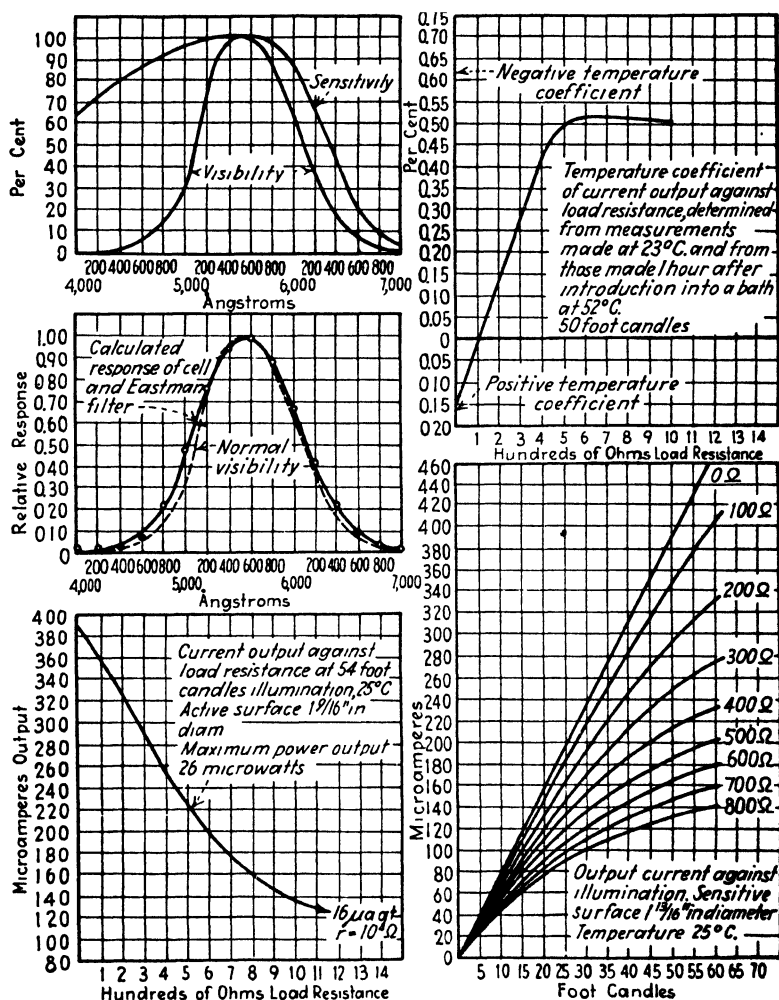
FIG. 27.—Quantitative data on General Electric blocking-layer selenium-platinum self-generating photocell.

The various cells differ largely in the manner in which connection is made to the light-sensitive surfaces. The present theory of operation is that electrons are ejected from one layer to the adjacent electrode when illuminated. If the electrodes are

connected through an external resistance, a definite proportion of the electrons pass through this load thereby establishing a current through it and developing a certain amount of power. The remainder of the electrons return to their starting point through the higher resistance across the interface.

Dr. E. D. Wilson, of the Westinghouse Research Laboratories, has spent some time on this interesting and promising phenomenon and it is from his paper that the facts presented here are taken. He obtained current of the order of 1 ma. by holding the cell close to a 100-watt lamp and several milliamperes in direct sunlight. By using a 3-ohm indicating instrument as a load, 10-ma. current was obtained. One of the best cells delivered 3 ma. through 100 ohms in direct sunlight. This represents a power output of 0.75 mw. per square inch or about 1 watt per square yard.

Commercial Copper Oxide Cell.—The Photox (Westinghouse) is a copper oxide photo-voltaic cell. It consists essentially of a copper disk oxidized on one surface, a transparent film of metal being deposited on the oxide. The disk is mounted in a molded case with two terminal connections. The transparent film is connected to one terminal, while the bare copper is connected to the other. Upon illumination of the cell through a glass window in the case, the copper becomes positive with respect to the film.

<div align="center">

TYPICAL CHARACTERISTICS

</div>

Short-circuit current .... 3 μa per foot-candle
Open-circuit voltage............ 0.35 volt at 50 foot-candles
Exposed surface............... 0.02 sq. ft.

Weston Photronic Cell.—A dry self-generating cell which came into active use in 1931 in an illumination intensity meter is the Weston cell. It consists essentially of a thin metal disk on which is a film of light-sensitive material. The metal disk is the positive terminal; a metallic collector ring in contact with the light-sensitive surface is the negative terminal. According to Weston engineers, there appears to be no chemical or physical change taking place when the cell delivers current upon illumination. The action seems to be purely electronic.

Current output, spectral sensitivity curve, etc., are shown. The current output is about 120 μa per lumen, or 1.4 μa per foot-

candle. The area of surface is about 1.7 sq. in. When measured by a potentiometer, the e.m.f. generated is about 7 mv. per foot-
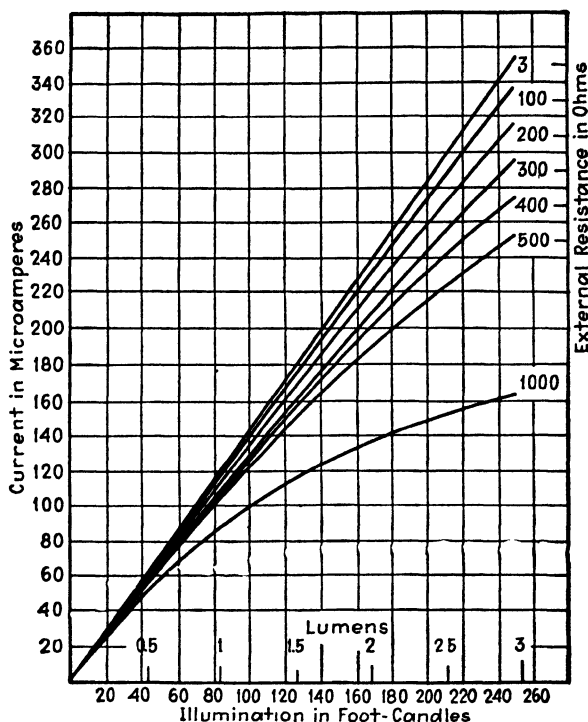
FIG. 28.—Characteristics of Weston Photronic cell.
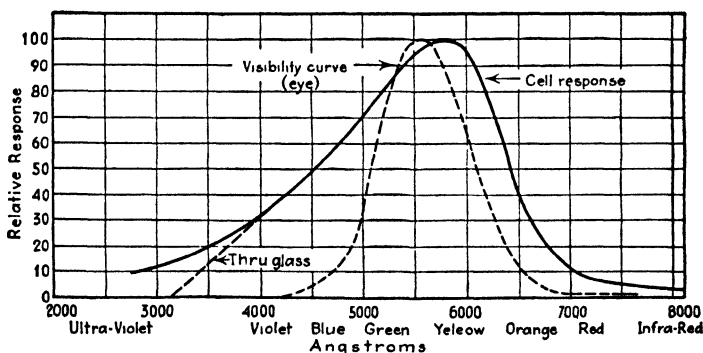
FIG. 29.—Comparison of Photronic cell and visibility of human eye.

candle at low intensities. The cell has some temperature effect, but this is small. The maximum variation from the output at

room temperature is 3 per cent. The voltage and resistance vary more than the current, however, and the manufacturers recommend that the current characteristic be used for illumination-measuring purposes.

The uses of the cell for illumination measurement will be discussed later. It is to be noted here, however, that such cells have very great promise as simple portable measuring instruments for the determination of light intensity. Several of the cells
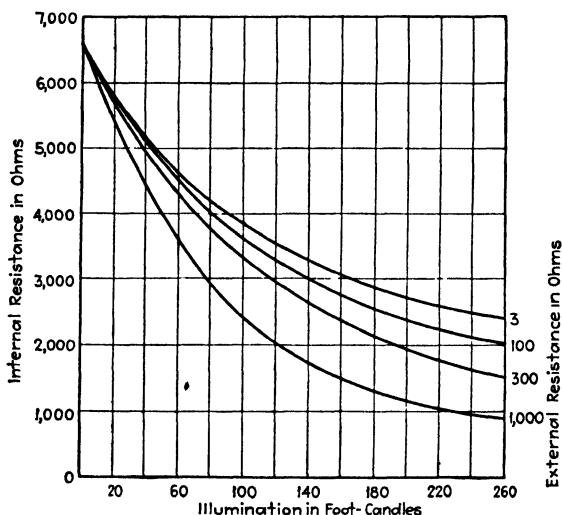
Fig. 30.—Internal characteristics of Photronic cell.

may be put in series or parallel, and when worked into a fairly low-resistance meter, the current output is linear with illumination. The cells are sufficiently rugged and stable in characteristic to be calibrated and used as accurate meters of illumination or of photographic exposure. The output power is sufficient to operate a sensitive relay directly.

The internal resistance of the cell is not a constant. It is of the order of 2,000 to 6,000 ohms decreasing with increasing light intensities and as the current through the cell increases. Since the resistance of the cell is high at low values of illumination, there is little object in operating two of them in series. Operating two or more in parallel, however, decreases the effective internal resistance and increases the sensitivity of a low-resistance device

using the cells. Illumination meters frequently use two or more of the cells to improve the sensitivity at low values of light intensity.

Relays for Use with Photronic Cell.—In using measuring instruments, galvanometers, or relays in connection with the cell of the type described above, the effect of the resistance of the meters must be considered. In most measurements, it is desirable to have an approximately linear response between the current produced and the light intensity. To obtain this, it is necessary to use an instrument of relatively low resistance, the value of which in turn depends upon the maximum intensity of illumination to be measured. For example, if the maximum illumination is say 250 foot-candles, a resistance of 200 ohms or less will be satisfactory. On the other hand, if the maximum illumination is 5 foot-candles, then instrument resistances up to 1,000 ohms or higher will give sufficiently linear response for practical purposes.

Relays usually require high torque to enable them to make reliable contact, and for this reason their resistances in general are considerably higher than in simple indicating instruments, and as a consequence, the action of a relay may depart considerably from a strictly linear relation, depending upon its resistance. This, of course, is not serious but must be considered in the design of the equipment. In fact, in instruments having a definite full-scale range in light value, advantage is often taken of the nonlinear characteristics of the cell with high external resistance, to increase the sensitivity for relatively low light values within the scale ranges. That is, the change in deflection per unit change in light value is greater in the lower part of the scale than in the upper part.

Comparative Output of Various Light-sensitive Cells.—Three types of light-sensitive cells were described above. They are (1) *photo-emissive*, in which electrons are emitted when a properly prepared surface is illuminated; (2) *photo-conductive*, in which the conductivity or ohmic resistance is changed by light; and (3) *photo-voltaic* in which an e.m.f. is generated by light. The photo-emissive tube has a very high resistance, delivers a large voltage change with small current change; the photo-conductive cell has a lower resistance (in general) and delivers a larger current change but smaller voltage change than the first type; the photo-

voltaic cell has still lower resistance and delivers a fairly large current change into a low resistance.

With regard to function, there are two considerations; the change in *power* effected, for operating a relay for example, and the change in *voltage* effected for operating an amplifier or gaseous rectifier for example. The photo-emissive cell will not operate a conventional electromagnetic relay directly. It will, however, deliver a large voltage change which may be amplified to operate a relay in the plate circuit of a vacuum or gaseous triode. The two other types of light-sensitive tubes will operate sensitive relays directly. Their output, however, in voltage can be amplified only with difficulty.[1]

Considering the selenium cell, a change in resistance takes place on illuminating the surface with light. This will permit a change in current through a series circuit made up of a battery, the selenium tube and a relay. The greatest change in current per turn per change in light intensity is desired. This will occur when the load resistance is equal to the resistance of the selenium tube. The power sensitivity (current change per unit change in light flux), is greatest near zero light flux.

Assuming an effective exposed area of 1 sq. in. and that a change of 20 per cent in light flux at an illumination level of 10 foot-candles is to take place, Dr. Wilson calculates that the current/turn change in a relay of 50,000 turns and 10,000 ohms resistance will be but 2 ampere turns. If 1 ma. current change is required to operate this relay (50 ampere turns), the selenium tube will not be able to move the armature.

If, however, the selenium cell is made to change the voltage applied to the grid of a tube by causing a change in current through a resistance, it is shown that the greatest change in voltage per light-flux change again occurs when the load and cell (dark) resistance are equal. Using a value of 1,000 megohms, 100 megohms as the series resistance, the drop across which actuates the amplifier tube, a change of 20 per cent in the light flux at the above intensity will produce a voltage change of

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[1] The following discussion of the relative outputs of these types of light-sensitive tubes is taken from a first discussion by Dr. E. D. Wilson, *Rev. Sci. Instruments*, December, 1931, and a later discussion in Zworykin and Wilson, "Photoelectric Tubes and Their Applications," 2d ed., John Wiley & Sons, Inc., 1932.

5 volts, sufficient to operate a relay in the plate circuit of an amplifier if properly chosen.

The caesium oxide photo-emissive cell is typical of modern practice. Considering such a tube in which the sensitivity is 15 μa per lumen the current per turn sensitivity figured as above is about 0.75 ampere turn per lumen or 5 times this roughly if a gaseous cell is used. This would produce a current per turn change of only 0.01 ampere turn into the 50,000-turn relay mentioned above.

The voltage sensitivity of the emissive-type tube, however, is much greater than the selenium tube and in the above case would produce about 20 volts change on the grid of the tube. This would operate a heavy relay in the plate circuit of a power amplifying tube.

A copper oxide photo-voltaic cell of 1 sq. in. active surface will produce only 0.005 ampere turn if it has a sensitivity of 100 μa per lumen, and an internal resistance of 500 ohms. Its voltage sensitivity is 0.05 volt per lumen. It has the advantage, however, that it converts directly radiant energy into electrical energy. No batteries or amplifiers are required. The voltage sensitivity mentioned above would produce only 0.0007 volt change on the grid of a tube with a light change of 0.0142 lumen at a level of 10 foot-candles. This grid voltage swing would produce a plate-current change of about 1 μa only.

A useful comparison of the Weston Photronic cell and the copper oxide type of cell will be found in C. H. Bartlett, Comparative Characteristics of the Copper-oxide and Photronic Cells, *Rev. Sci. Instruments*, October, 1931. The fundamental differences in the internal resistance of these cells and the manner in which this resistance changes with variations in illumination produce a difference in the manner in which the cells operate in practical circuits. The effect of the change in internal resistance with illumination must be taken into account when circuits are designed for them.

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CHAPTER VI

APPLICATIONS OF LIGHT-SENSITIVE TUBES

The introduction of the light-sensitive cell to the service of industry smacks, to the lay mind at least, of the startling. It is one of the "marvels" of science. It is incomprehensible that a beam of light (perhaps an invisible beam of light at that!) should start or stop a piece of heavy machinery, a printing press turning out a thousand papers a minute, perhaps protect a box of jewels from theft, turn on an automatic sprinkler system in case of fire—all this is as incomprehensible as getting music from the silent "air" a few years ago. The phototube and its companions, the amplifier and the controlled rectifier, will not only perform stunts but will control staid processes in less time, or more cheaply, or with less danger to life or limb than older processes. It will perform functions not now possible with existing mechanisms, all through the medium of a beam of light.

The concept of using light as something besides a means of illumination is new; factory managers feel it a little too uncanny for introduction into a plant. They feel that radio tubes will wear out, light sources will lose their illumination or burn out, phototubes will deteriorate—but mechanical units have definite lives too, and often experience all of the ills of moving parts.

At present there are thousands of light-sensitive units in operation and the future will see extended application. It is not too much to hope that through the medium of light-sensitive surfaces, converting luminous radiation into electricity, the sun's beneficent energy may be put to still greater use by man. This conversion proceeds at a very inefficient rate today; the ideal cell, according to Zworykin and Wilson,[1] should deliver about 66 ma. per lumen. But cells actually produce only one-thousandth of this current. Lange calculates that one square meter of silver selenide should produce 1 watt of electrical energy.

[1] "Photoelectric Cells and Their Applications," 2d ed., John Wiley & Sons, Inc.

But on each square meter of the earth's surface the sun pours about 2 kw. of energy.

A statement must be made about the reliability of the amplifier and phototube. Tubes of various types have been in service long enough to demonstrate their thorough reliability. The railroads have in operation over 12,000 amplifier tubes. Records indicate that these tubes have an average life approaching 3,000 hours. A 25-watt incandescent lamp, with a life of 1,000 hours, is considered reliable. It operates at a filament temperature of 4000°F., has a filament approximately 20 in. long and 0.00118 in.
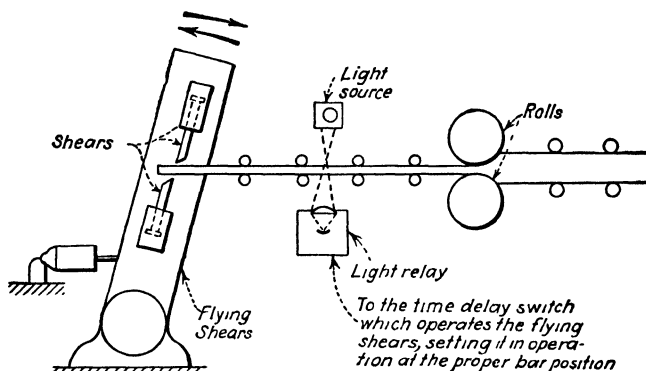
FIG. 1.—Automatic shearing apparatus using light-sensitive relay.

in diameter. The filament of the train-control tubes operates at 3140°F., has a much larger filament, 2 in. long and 0.004 in. in diameter—about ten times the cross section of the lamp filament. The sturdiness of this filament and its lower operating temperature are both in the direction of long life and freedom from filament breakage.

In elevator service, the tubes will probably last much longer than this figure of 3,000 hours. Although the filaments are heated continuously, the tube is loaded only when the elevator is leveling. Furthermore, such tubes are much less subject to vibration.

If the voltages and light intensities used with phototubes are kept below the manufacturers' ratings, long life can be expected. In fact, the manufacturers of some voltaic cells claim "unlimited life." Gaseous emissive-type cells have a shorter life than vacuum cells, but in either case the life is such that economical operation is easily possible.

It is true, of course, that the lamp which projects the light beam will burn out, and that the electron tubes will in time reach the end of their useful life. Such matters can be controlled reasonably well, however, by a proper understanding and application of the equipment and regular systematic replacement. High-intensity lamps, for example, when operated at their rated voltage have only a few hundred hours' life. If the voltage is decreased to 85 per cent of the rated value, the life will be increased about tenfold, whereas the light will be decreased
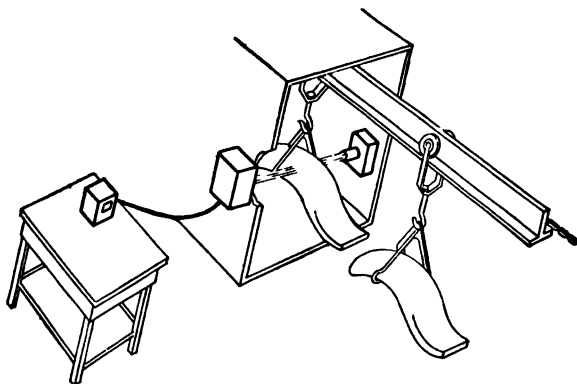
Fig. 2.—Counting freshly painted objects.

less than half. Thus by using a lamp about twice the size that would be required if it were burned at full brilliancy, the requisite light and ten times the life can be obtained by operating it at reduced voltage. This is standard procedure.[1]

The possible applications of the photocell are "limited chiefly by the imagination of the user."[2] They all depend upon the fact that light shining on the light-sensitive surface causes the production of, or some change in, electrical energy. This energy can be used directly, through a sensitive relay, or can control amplifiers or controlled rectifiers. In many cases the phototube current is used to indicate light intensities directly, for example, in colorimetric or photometric work, or, by the proper calibration, the device may be used to indicate photographic exposures over a wide range of light intensities.

[1] On life to be expected in service, see *Electronics*, "Crosstalk," July, August, and September, 1936.

[2] KOLLER, L. R., *J. Optical Soc. Am. and Rev. Sci. Instruments*, September, 1929.

General Types of Application.—Thus there are several distinct types of use for light-sensitive cells. There is that class of use where only a simple on-and-off effect is desired, for example, the turning on of street lamps at dusk, or the stoppage of machinery where a light beam is affected, say, by a break in a printing press paper roll. There is the type where a varying light input intensity produces a varying effect, as in photometry; there is a selective effect, by color for example, where objects are sorted because their different color reflects widely different values of light into a tube sensitive to a particular color.

Perhaps the earliest application was to the photometry of lamps. A number of photo-electric-cell photometers are at present in actual operation.[1] With slight modifications, the phototube takes the place of the eye at the photometer head and so eliminates the human equation. One of the difficulties encountered is the fact that the color sensitivity of the cell differs from that of the human eye so that the cell does not evaluate correctly when lights of different colors are to be compared. This can be compensated for by suitable color filters adjusted to the cell.

The photocell is also used in studying and making continuous records of variations in light intensity, daylight or artificial. Quartz cells with cathodes which are not sensitive to visible light are used for measurements of the ultra-violet in the solar spectrum and for studying other sources of ultra-violet. Such a cell is a valuable aid in determining quantitatively the amount of ultra-violet obtained from the various sources used for therapeutic work[2] and in measuring the deterioration of such sources.

Photocells have also been used in a device by means of which a complete quantitative spectrophotometric analysis is made of any reflecting surface. They are convenient tools for making measurements of the transmission or absorption of liquids, solids or gases and will respond to differences which cannot be detected by the eye. An excellent short paper, nontechnical, on the application of phototube controllers will be found in the *Electric Journal*, October, 1935, by E. H. Vedder. The author discusses simply how objects are made to interrupt a light beam, how liquids of varying refractive index or transmission may affect

[1] LITTLE, W. F., and C. E. HORN, *Trans. Ill. Eng. Soc.*, 1927.
[2] See WOLF, L. J., *Electronics*, June, 1936, Ultra-violet Recorder.

control, the effects of temperature on the phototube equipment, how colors affect control, and other most pertinent facts of interest to one just developing an interest in electronic control.

Applications include cigar sorting; airport lighting; traffic control; railway signal control; elevator control; testing of dyes, quality of papers, oils, etc. In general, practical photo-electric-cell applications may be divided into two groups: control devices and indicating quantitative measuring devices. In the first type of application they must respond to a change in light intensity, which may be quite large, and operate a relay or a
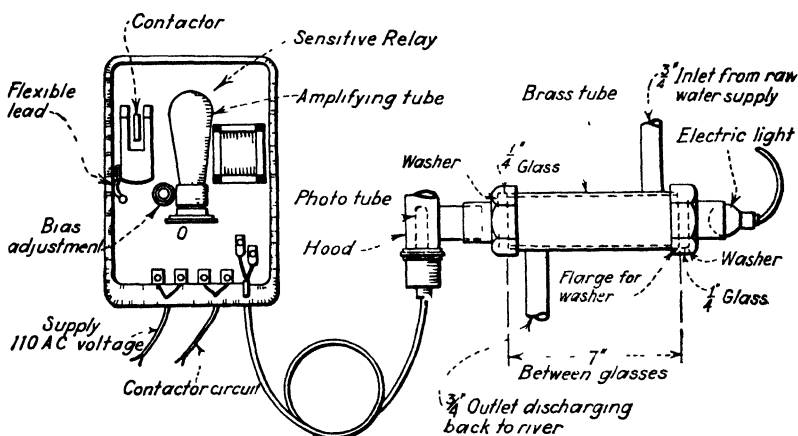
FIG. 3.—Photocell and lamp for detecting turbidity in Denver water supply.

tube by means of which other apparatus is controlled. In the other type of application they may be used to perform a chemical analysis, as, for example, by measuring the absorption or reflection of light by a sample of material, to make spectrophotometric measurements or to photometer lamps, or indicate correct photographic exposure.

Accurate count may be secured with an interruption of the light beam lasting only one-twentieth second. With a like period between light interruptions, it is possible to count as high as 600 per minute without any contact-making devices or moving parts other than the magnetic counter which is energized directly by the controlled-rectifier tube.

The applications where an interrupted light beam produces an industrial control, other than counting or sorting, are very com-

mon.   In general these uses do not differ from the general types described.   One of the great advantages of systems of control using a beam of light is the fact that no power is required to interrupt this beam.   Furthermore, since the change in light produces an electric current change which can be transmitted to any distance by wires, the actual control apparatus may be at some distance from the system to be measured or controlled. A good example is remote metering or registering of the number of units passing a certain point in a production line.
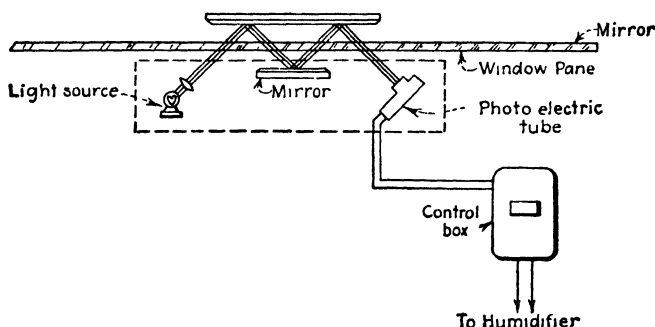
Fig. 4.—Water condensing on window pane changes light reflected into photocell and operates humidifier.

Comparison of the Types of Light-sensitive Tubes.—The emissive type has come into widest use, probably because it reached its highest development first.   It is characterized by a high internal resistance and a high terminal voltage but capable of delivering but little current to an external load.

Because relays of the electromagnetic type require a high current and comparatively low voltage for successful operation, some intermediate device must be employed between the photo-tube of the emissive type and the relay.   The ideal coupling unit is an amplifier tube because its input circuit is adapted to *receive* power from a high-resistance source (the phototube) and its output circuit is adapted to *deliver* power to a low-resistance load (the relay).

If a phototube of the emissive type could be developed so that it would deliver sufficient power to operate a relay directly, even though it retained its characteristic high internal resistance, relays might be designed to operate directly from the cell; but unless relays of hundreds of thousands of turns could be made,

much power would be lost in the transfer from tube to relay. This is due to that fact discussed in Chap. V that maximum current change is transferred from a tube to a relay only when the respective resistances of the two devices are of the same order.

In general, then, the phototube of the emissive type is operated with an amplifier and thence into a relay. The amplifier tube serves to match the resistance of the relay to the light-sensitive cell and in addition provides the additional power necessary to operate the relay and at present unobtainable from the best of the phototubes.

This statement may not be true in the future. If a relay can be developed which requires a high voltage but very little current, it can be operated directly from a photo-emissive tube. For example a piece of Rochelle salt crystal is strongly piezo-electric, that is, it is mechanically deformed when voltages are placed on its surfaces. Relays have been devised using this principle; the 10 or more volts obtainable from a phototube, applied to the surfaces of the piezo-electric crystal, produces mechanical motion of a properly coupled armature which closes or opens electrical contacts.

Furthermore, already in the laboratory are relays which operate on an electrostatic principle requiring a large voltage change but little current. These relays operate directly from a phototube. One such device has a metallic plate which is held tightly to a charged surface so long as the phototube is illuminated (because the output current of the tube charges the surface electrostatically) but when the beam is eclipsed, the charge is permitted to leak away and a spring pulls the metal plate away from the surface. Interrupting the beam of light releases the armature which then opens or closes contacts.

The photo-conductive cell (selenium) has a medium resistance, of the order of several or many thousand ohms, compared to the megohms resistance of the emissive type of cell. Therefore it can be operated into a relay directly.

The photo-voltaic cell has a much lower internal resistance, usually of the order of 500 ohms more or less. Its current output, therefore, is much higher than the emissive cell: milliamperes compared to microamperes. Its power can be more efficiently transferred to an electromagnetic relay than that of an emissive-type cell and therefore these tubes are worked into relays directly.

Owing to the low internal resistance of these tubes their output voltage cannot be amplified successfully.

When illuminated with modulated or interrupted light, the foregoing statement is not true, for then a transformer with proper primary and secondary turns may be used to match the cell to the amplifier so that appreciable voltage is transferred to the tube amplifier.   In general, however, in industrial application

(a)

(b)
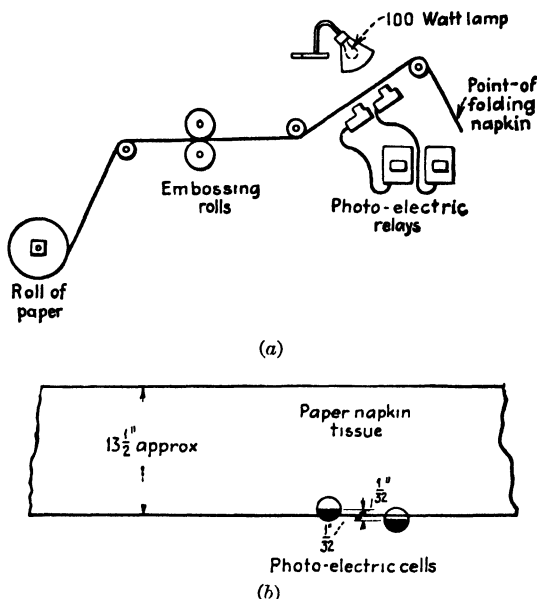
Fig. 5.—(a) Sketch of a paper-napkin cutting and folding operation in which the paper alignment is checked by two phototubes.   (b) Location of the phototubes with respect to the guiding edge of the paper.

the beam of light is not modulated and therefore the photo-voltaic tube is operated into a sensitive relay whose contacts usually close a power relay capable of handling whatever power is ultimately to be controlled.

The emissive type of phototube can be made sensitive to various portions of the visible, or infra-red or ultra-violet spectrum.   Modern cells are quite sensitive to the red end of the visible spectrum where lies the greatest emitted energy of the incandescent lamp.   Photo-conductive and photo-voltaic cells have more or less the same spectral sensitivity as the human eye and can be made to approach it quite accurately.

The vacuum emissive type has an output that is linear with respect to light intensity; its output is changed less by temperature changes; it is exceedingly fast because there is no inertia to the motion of electrons through the tube; and it is very stable with time.

What Cell to Choose.—Having a task for a phototube, it becomes necessary to choose the type of cell to be used. If considerable light changes are available, such as a complete eclipse of daylight or of concentrated light from an incandescent lamp, the voltaic cell of the dry-disk type operating a sensitive relay directly may be used successfully. If the light changes are small, it is best to use an emissive type so that the voltage changes may be amplified and then applied to a relay.

One of the merits of the dry-disk type of voltaic cell is the fact that it need not be close, physically, to its relay. The emissive type of tube is a high-resistance device and cannot be operated much over 15 ft. from its amplifier tube, especially when operated from alternating current. On the other hand, the voltaic cells in common use are low-resistance devices and may be placed many feet from the relay they control.

COMPARISON OF MERIT OF THE THREE TYPES OF LIGHT-RESPONSIVE CELLS

The photo-emissive cell is in most general commercial use for the following reasons:

1. High red sensitivity.
2. Stability.
3. High impedance resulting in high voltage output.
4. Linearity of response.
5. Good dynamic response.
6. High speed.

Its principal limitations are:

1. It generally requires amplification in relay equipment.
2. It requires an operating potential of 50 volts or more.
3. Operating current should be limited to not more than 50 μa—generally less.

The advantages of the photo-conductive cell are:

1. Some types can be made very sensitive to infra-red light.
2. Some types have large current output (with low sensitivity).
3. Some types have high sensitivity with low current.
4. Can be operated at low voltage.
5. It has good response in all parts of the visible spectrum.

Its disadvantages are:

1. Some types are unstable.
2. It has a rather high dark current.

3. Its time lag is often great, and dynamic response is usually poor.

4. It is frequently critical with respect to operating voltage.

5. It has a considerable temperature coefficient.

The advantages of the photo-voltaic cell are:

1. It operates without external source of voltage and is particularly suitable for portable use or installations where 110-volt power is not available.

2. Can be used with relays without amplification if sufficient change in light intensity is available.

3. Two or more cells can be conveniently used in parallel or series.

4. Relatively large output currents can be obtained.

5. Some types are stable over long periods.

6. Color response is similar to that of human eye.

The limitations of this type are:

1. Its output cannot be conveniently amplified by vacuum-tube methods.

2. Since the output cannot be efficiently amplified when used with relays, the relays required are of low torque (resulting in low contact pressure and relatively slow speed of operation) and are expensive.

3. For relay operation relatively large changes in illumination are necessary.

4. Some types have a considerable temperature coefficient.

5. Ambient temperature range is somewhat limited.

6. It has appreciable lag of response.

Amplifiers for Photocells.—The currents from an emissive-type photocell are so small that they are incapable of doing much
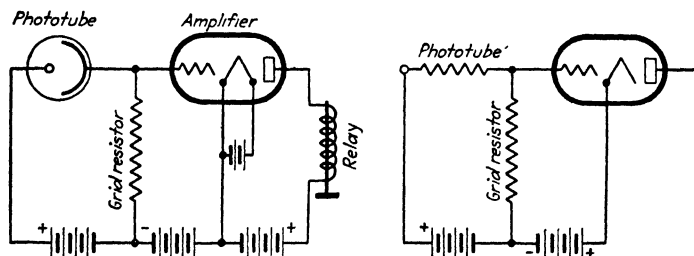
Fɪɢ. 6.—Phototube plus amplifier and equivalent circuit. Light on the photo-tube will increase the amplifier current.

work; from the best type of commercial cell 10 in. from a 60-watt tungsten lamp only about 10 to 20 μa may be obtained. Therefore these currents must be amplified before they can operate a relay or do any other useful work.

Consider the simple amplifier shown in Fig. 6. The grid resistance may be of the order of 1 to 10 or more megohms. Since there is no current flowing between grid and filament, so long as the grid is negative, there is no voltage drop along this

resistance and the entire battery voltage is impressed between grid and filament, maintaining that grid negative with respect to the filament. If, however, by any means this voltage may be increased (made more negative) or decreased (made less negative) the plate current will change. This change may be sufficient to operate a relay or it may be amplified again and finally operate a loud-speaker as in the sound-picture industry.
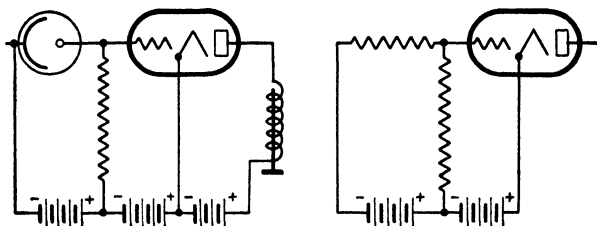
FIG. 7.—Circuit in which light causes decrease of amplifier current.

It is the function of the photocell to effect this change in grid voltage and thereby produce plate-current changes. The photocell can be connected in two ways, either to increase the current in the plate circuit when light falls upon the cell, or to decrease this current. In Fig. 6 the current will increase and in Fig. 7 it will decrease. The reason is as follows: In the equivalent circuit of Fig. 6 the photocell is replaced by a resistance which
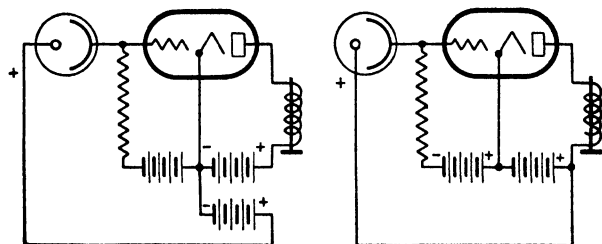
FIG. 8.—Method using single battery for phototube and amplifier.

varies in value with the intensity of light falling upon it. If the cell is short-circuited, the entire battery voltage of the cell battery will be impressed across the grid resistance and will make the grid positive because the cell battery is connected in a direction opposite to the grid battery.

Therefore if the photocell is in the circuit and light falls on it, current will flow through the photocell and the grid resistance.

The sum of the voltage drops across the photocell and the grid resistance must be equal to the battery voltage. The voltage drop across the grid resistance is not the entire battery voltage but only a part of it, (if the grid resistance is 1 megohm, this new grid voltage will be 1 volt for each microampere of photocell current), but whatever this voltage is, it is in a direction opposite to the grid battery and therefore the voltage between grid and filament becomes *less* negative and more plate current will flow.

Now in the equivalent circuit of Fig. 7 it will be seen that the two batteries are in series and, if the photocell is short-circuited as before, one of the batteries is directly across the grid resistance. This will not affect the voltage between grid and filament any more than the voltage will be affected at the ends of a circuit consisting of two batteries in series if a resistance is placed across one of the batteries. Therefore when the photocell is in operation and current flows from it, it flows in such a direction that some of this photocell voltage is available to be added to the grid voltage and will, therefore, make the grid more negative with the result that less current will flow in the plate circuit.

Since the anode of the photocell must be maintained positive with respect to the cathode or emitter of electrons and since this voltage is of the same order as the plate battery of the amplifier tube, the same battery may be used as shown in Fig. 8, where the same circuit is drawn in two ways, one with an additional battery, and the second with the same battery serving two purposes. The results will be exactly the same.

The engineer connecting up for the first time a triode amplifier need not worry, as some seem to do, about the various batteries and circuits and whether current flows from one into another if he remembers that the grid-filament path through the tube is of exceedingly high resistance so long as that grid is negative and therefore cannot collect electrons. No current will flow between grid and plate because there are no electrons leaving the grid to go to the plate, unless by some chance it becomes hot enough to emit them. Therefore the engineer accustomed to working with tube circuits never thinks about the fact that between grid and plate may be a high voltage consisting of the plate battery and the grid battery in series. He considers that the grid circuit is distinct, that the plate circuit is distinct, and that the filament circuit is distinct. It is true that the plate

current must flow through one-half of the filament wire but in general this makes no difference in the operation of the circuit. The filament current is usually of the order of an ampere while the plate current is of the order of a thousandth of this value.

In tubes with heavy plate currents and low filament currents (seldom used) the plate current may amount to one-tenth of the filament current so that one-half of the filament runs hotter than the other and such tubes usually fail by this half of the filament breaking. On the other hand, it has become almost universal practice to operate the filaments of modern tubes from alternating-current circuits so that on one half-cycle the plate current flows through one leg of the filament and on the other half-cycle it flows through the other leg.

As an example of the operation of phototube plus amplifier consider a circuit in which the grid of the amplifier is biased 25 volts negatively and a plate current of about 1 ma. flows through the relay, not sufficient to close it. When the phototube is illuminated, current flows through the grid resistor of the amplifier (50 megohms), and through the relay. This current may be as low as 0.3 μa and, of course, would not be sufficient to cause any change in the position of the relay armature. This current, however, flowing through the grid resistor causes a voltage drop along it of 15 volts which is in such a direction as to decrease the negative grid bias to 10 volts. Under such a condition the plate current would increase to 8 ma. and the relay would operate. An illumination intensity of about 7.5 foot-candles would produce this current change in an average high-vacuum cell.

Direct-current amplifiers described in Chap. III may be used with phototubes. Multistage amplifiers are rarely necessary. An emissive-type phototube will change the bias of an amplifier tube over appreciable changes even with slight illumination, and the difficulties with instability when more than a single, or at most two, stages of d.c. amplification are used make it simpler to modulate the light and then amplify it to the desired value. In this case a.c. amplifiers may be used.

Operation of Phototubes and Amplifier from Direct-current Power Circuit.—It is possible, and generally preferable, to secure the necessary voltages for operating the phototube and its associated amplifier directly from a source of 110 volts direct or

alternating current than to use batteries. The latter are cumbersome and wear out.

The circuit in Fig. 9 shows the operation from a source of 110 volts direct current. The filament of the amplifier is placed in series with sufficient resistance to reduce the current to the proper value and is placed directly across the line. The disadvantage of such a circuit compared to a.c. operation lies in the fact that much heat must be dissipated in this series resistance. Thus if the tube takes 1 amp. at 2.5 volts, the heat must be that corresponding to $110 - 2.5$ or 107.5 volts $\times$ 1 amp., or 107.5 watts, while the tube filament itself consumes but 2.5 watts.

The voltage drop along the resistance in the positive side of the line constitutes the plate voltage of the tube; the voltage drop in the other resistor is the voltage required for the phototube. The grid of the tube may be biased negatively, or connected directly to the cathode, depending upon where it is connected to the resistance in the negative side of the line. If the grid is connected to the cathode directly, it will not be negatively biased and some current will flow in the anode circuit. Therefore the relay will be closed. If the phototube is illuminated, its current will set up a voltage opposing the voltage across the grid leak due to grid current. This will make the grid negative, cut off the plate current and release the relay.

Fig. 9.—Direct-current operation of phototube and amplifier.

In addition to the wastage of power and heat there is one other disadvantage to operation from 110-volt d.c. circuits. This is the fact that a limited voltage is available for the plate circuit of the amplifier.

It is more economical to operate the photocell and amplifier from an a.c. source, for in this case transformers may be used to supply exactly the correct voltages for cathode, grid and plate, and phototube without waste of power.

Alternating-current Operation of Photocells.—Since both the phototube and the amplifier are rectifiers, in that they pass current only when the anode is positive, a circuit like that of

Fig. 10 may be operated from alternating current. Here the filament of the tube is operated from a 6-volt winding on the power transformer; another winding supplies a voltage which can be utilized as a negative bias for the power tube, and a third winding supplies a positive anode voltage for both the amplifier and the photocell. Actually the grid and anode windings are one continuous winding, the center of the filament winding being properly connected to the grid winding so that negative voltages are available. Current flows through the two tubes only on the half-cycles which makes the two anodes positive with respect to the filament.
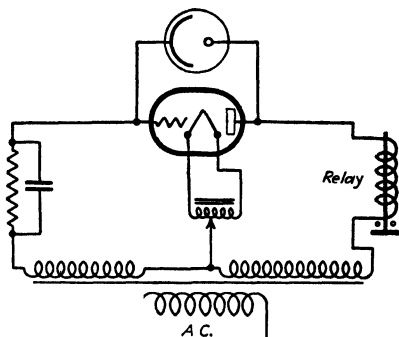
FIG. 10.—Alternating-current operation of light relay.

A typical a.c. operated system is shown in Fig. 10. In this case when the plate is positive, the grid is negative; variations in the illumination of the phototube, however, change this nega-
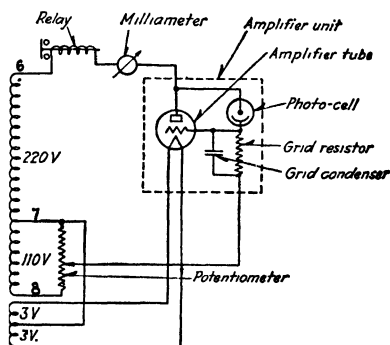
FIG. 11.—Commercial a.c. operated phototube-amplifier.

tive bias and produce a change in the plate current. The purpose of the grid condenser is to decrease the grid bias required to reduce the plate current to a given value when the photocell is dark. The negative grid voltage is out of phase with the plate voltage when high values of grid resistance are used, thus making ineffective the grid control. This is due to the input capacity

of the tube in combination with the grid resistance. The condenser brings more nearly in phase the effective grid bias and the plate voltage.

One way to avoid troubles of d.c. amplification, as when amplifying the output of a photocell with low values of illumination, is to modulate the photocell output and then use an a.c. amplifier. Richter[1] has shown one such circuit (Fig. 12).
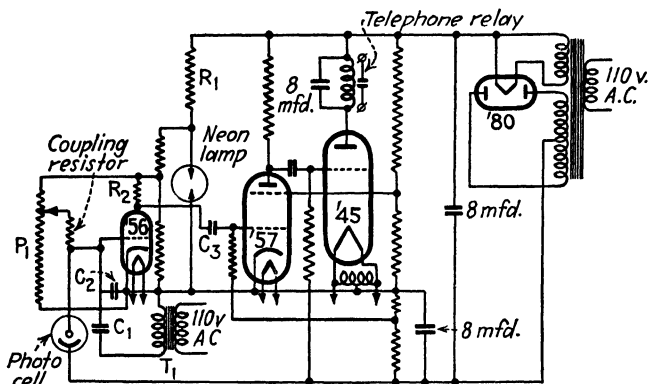
FIG. 12.—Amplifier produces d.c. amplification on an a.c. basis by a modulating scheme.

Relays for Use in Electron-tube Circuits.—Applications of light-sensitive tubes falling into the group in which a beam of light is obstructed require an electric relay whose contacts open or close an electric circuit. This relay may operate directly from the phototube (if of the low-resistance, high-current type such as the dry-disk types) or from either an amplifier tube or a controlled-rectifier tube.

These relays differ from those conventionally found in other electric circuits. They must be designed to operate under the special conditions imposed by electron tubes as sources of power. In general those relays which operate directly from phototubes are sensitive and not capable of handling much power by themselves. If, however, their contacts close a second relay, this latter device may handle almost as much power as is desired.

The relays customarily used are either telephone relays or resemble them. Since the currents available from phototubes

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[1] *Electronics*, August, 1935. This application was in furnace-temperature regulation.

of the voltaic type or from amplifier tubes are only of the order of a few milliamperes, these relays must be designed to pull up on small currents.   Relays of the type used in power electrical circuits cannot be used for the electron-tube circuits, except as secondary contactors.

Relays are often spoken of as a "1,000-ohm relay," etc.   The reason is as follows: Since the currents available are so small, the coils of the relays must be made of many hundreds or thousands of turns of fine wire wound in small space.   Even though copper wire is used, the resistance is high, perhaps of the order of 10,000 ohms.   The shape of the coil and the wire size are chosen to secure the maximum pull on the armature with the current available (*i.e.*, the maximum ampere turns); the high resistance is inevitable and not desirable.   Thus the relay designer does not deliberately construct a relay with so-many ohms resistance— he could do this very simply by using high-resistance wire. His task is to get the maximum possible ampere turns in a small space so that a highly concentrated and powerful field is available to pull up the armature, and to hold it against a spring or gravity or the force of the contacts so that the contacts do not waver or chatter or fall apart.

Such relays require a certain minimum current to pull-up. They should have a high drop-out value.   Any relay will drop out if the current through it is reduced to zero, but this requires either a large light change, if the relay operates directly from a phototube, or a large grid-bias change if it operates in the plate circuit of an amplifier.   What is desired is a relay which pulls up on little current and drops out on a small decrease in this current.

Most of the telephone-type relays are designed to drop out on values of current one-half their pull-up values.   Such relays are fast in operation, for example a typical relay pulled up in less than 0.01 sec., released in 0.02 sec.   It requires 3 ma. to close contacts, 0.8 ma. to release.

More sensitive relays are often required in electron-tube circuits.   They are usually of the meter-movement type and will operate on currents as low as 15 μa, will handle 0.2 amp. at 6 volts, and have resistances of the order of 1,000 ohms.

Various contact combinations are provided by relay manufacturers, varying from the simplest consisting of merely two contacts which are opened and closed with the action of the

armature to much more complex systems of contacts which open or close several circuits which are the equivalent of three-pole, double-throw switches. Such relays require more coil energy than the simple relays.

The coil of these relays is a rather high inductance since it is composed of many hundreds of turns of wire wound on an iron core. Therefore at break a severe spark will occur due to the induced e.m.f. This spark will harm the contacts unless precautions are taken such as shunting a resistance across the contacts. A neon lamp across the contacts will absorb this inductive power and prevent destruction of the contacts.

Relays with high drop-out currents compared to the pull-up values are advantageous when the phototube is surrounded with extraneous illumination. In this case the change in illumination when the light beam is interrupted is not so great as if no light gets to the tube other than that from the desired beam.

Dry-disk Cell Applications.[1]—The simplest types of application are found employed with the dry-disk cells. In fact the great advantage of this type of light-sensitive tube lies in its simplicity and in the simplicity of putting to use its output.

There are many applications, for example, where linear response is not required at all frequencies, such as, for instance, in the measurement of projectile velocity. The U.S. War Department has built a device using dry-disk photo-electric cells to detect the passage of a rifle bullet at speeds up to 3,000 ft. per second with an accuracy of plus or minus 1 ft. per second.

The internal resistance of this cell (Weston) is relatively high, varying from 6,000 to 7,000 ohms for a dark cell to 1,000 to 2,000 ohms under intense illumination. This condition allows the use of fairly high-resistance meters in the external circuit and accounts for the fact that lead resistance is negligible and that therefore the cell may be mounted any desired distance from the meter or relay. This characteristic was taken advantage of by the engineers for the Holland tunnel under the Hudson River; they mounted a cell in the middle of the tunnel and had it record smoke density at that point, on a recorder in the New York control room, over 3,000 ft. distant.

[1] See LAMB, ANTHONY, *Elec. Eng.*, November, 1935, and FOGLE, M. E., *Electrochem. Soc.*, *Preprint*, No. 69–15, paper presented at Cincinnati, April, 1936.

Like the emissive type of cell, the dry-disk type may be used in the three fundamental groups, *i.e.*, where the light is completely eclipsed, where there is a change in light, or where there is a change in color. In the first group is the simple task of counting objects or in opening doors. Figure 13 shows the arrangement of cells in a typical door-opening scheme where a diagonal beam of light is used to prevent the doors' closing if a person remains in the main beam.

As shown in Fig. 13, there are three cells connected in series, cells 1 and 2 being operated from either approach, and cell 3
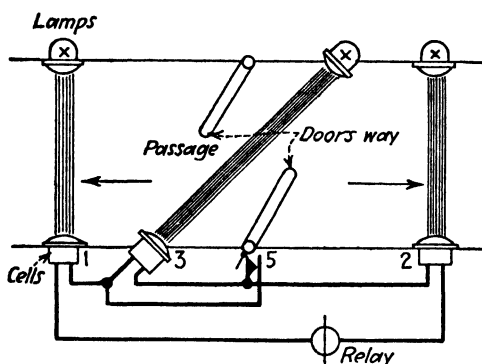
Fɪɢ. 13.—Door-opening setup.

being used to hold the door open when anyone remains in the doorway. When the door closes, cell 3 is short-circuited by the switch 5. The dark resistance of the cell is five to six times that of the cell when illuminated; therefore, when the door is closed and cells 1 and 2 are connected in series, blocking either light beam will reduce the output current practically to zero and thus operate the relay. Likewise, when the door is open and all three cells are in series, blocking the diagonal beam or either of the other beams will cause the relay to close and the door to remain open.

A good example of the utility of this type of cell for changes (not complete cut-off) of light is in warning an attendant when improper combustion is taking place in a power plant. A beam of light is sent through the stack into a cell. When a predetermined amount of smoke obscures the light to a certain degree, the change in current output sets off an alarm which continues to ring until the maladjustment is corrected.

The diagram of a photoelectrically controlled process for regulating the amount of dissolved silver in the hypo fixing bath, for use in large-scale film copying, is shown in Fig. 14. The object of the process is to keep the silver content below a given maximum value so that the films will not be injured by discoloration, as well as to recover the valuable silver. Spent hypo is removed continuously from the fixing tank, and a precipitating agent added to remove the dissolved silver. The silver precipitate is removed in a filter press, and the clear liquid returned to the storage tank. A small sample of the filtrate from the first
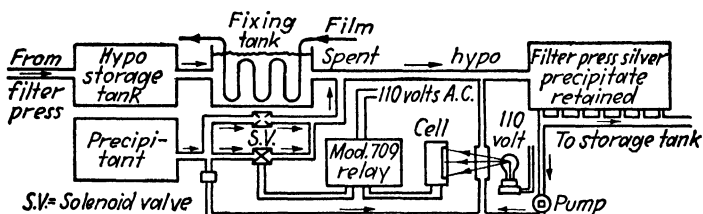
Fɪɢ. 14.—Diagram of process for controlling silver content of hypo fixing solution.

section of the filter press is mixed with more precipitant before passing through the light beam falling upon the photocell. The amount of precipitate formed in this solution depends upon the amount of residual silver in the sample of hypo. The output of the cell goes to a relay control unit, having high and low limits, which controls a solenoid bypass valve on the precipitant being added. The silver content can be regulated within close limits by proper adjustment of the relays.

Inasmuch as there is little engineering involved in such simple problems other than securing the proper source of light (to be detailed later) and the mechanical arrangements naturally necessary to fit the phototube and relay to the job, a detailed account of these operations will not be given. The installation of the voltaic type of tube plus its sensitive relay, operating a larger relay in turn, involves mechanical rather than electrical engineering.

These simple types of circuits are admirably adapted for straight on-and-off applications where sufficient light is available to produce from the tube the required current to operate the relay. In addition to these simple uses, this type of tube may

be employed in more complex arrangements, and a number of these will be found described below.

Applications of Emissive-type Tubes.—In general the voltaic-type tube requires a larger change in light intensity because of the inability to amplify its output effectively. Therefore, where the illumination is not of the value required by the voltaic tubes, the emissive-type tube is employed. These tubes require an amplifier or a gaseous-relay tube.

Many of the applications performed now by emissive-type tubes with amplification may be handled by voltaic tubes with a sensitive relay. The relative economy and simplicity of the two methods depend upon conditions. In one case, the engineer deals with a phototube, an amplifier and a relay. In the other case, he deals with a phototube, a sensitive relay, and the power relay. Thus the sensitive primary relay in the latter case replaces the amplifier. Only time will tell in a particular installation which will get out of order sooner, or which will be more satisfactory, provided of course there is sufficient light change to operate the voltaic cell system. If the light is weak the emissive tube plus amplifier *must* be used.

Phototube Plus Amplifier Tube.—The photocell is not able to do much by itself, its power output is too small. But when it operates an amplifier tube of the high-vacuum type or a relay tube of the gaseous-triode type, the possible applications seem to be beyond count. A typical example of high-speed control made possible by a beam of light, a phototube and a pair of grid-controlled rectifiers may serve as a single example of the utility of electron tubes in industry. The example is in the cutting of paper with printed matter previously imprinted on it. The slipping, stretching, and shrinking of the paper necessitate some form of control to assure cutting in registry with the printed matter. Each imprint includes a small spot that passes before the phototube and reduces the light reflected into it from the surface of the paper. The resultant change in phototube current is amplified and applied to the grid circuit of two gaseous controlled rectifiers.

Attached to the rotary knife is a rotary selector switch. This switch is also connected in the grid circuit of the two tubes, and if the knife is in its proper position when the spot passes before the phototube, neither of the two gas tubes passes current.

If the knife is ahead of, or behind, its proper position when the spot passes the phototube, one or the other of the tubes is almost instantaneously energized and operates the necessary control equipment to change the relative speeds of the paper-feed rolls and the cutter knife.

Since the paper often travels as fast as 500 ft. per minute and the spot is only a fraction of an inch long, it is apparent that the time allowable for energizing the tube circuit is only a few thousandths of a second. The tube can respond in this time, however, and continues to pass current until the proper control function is completed, when its circuit is opened automatically. The system which has been successfully applied in this particular application is capable of responding to light impulses or interruptions as short as fifty millionths of a second.

Phototube Counting Systems.—The simplest use of the phototube and relay (with or without amplification) is that of counting. A beam of light shines across a conveyor belt into a phototube which operates a relay or counter. When the beam is obscured by one of the objects to be counted, the change in tube current operates the counter. If it is desired to count large objects as well as small ones two phototubes may be arranged, horizontally or vertically, so that when both are obscured one count is made, but when only one is obscured another count is made. Thus the large objects shutting off the light from both tubes will operate one counter; smaller objects eclipsing only one tube operate a second counter. Of course, as an alternative arrangement a mechanism may be arranged which will separate the two objects, and thus the counting system becomes a sorting system.

The circuit[1] shown in Fig. 15 will give a production supervisor a record of the efficiency of an operator by counting the empty and full containers on a conveyor belt. Each time the belt brings a pocket or bin under the phototube a mechanical switch *Sw* closes the circuit. Then if the bin is empty, counter *E* records the fact; if the light is interrupted so that the phototube suffers a change in output, counter *F* registers this fact, because the relay closes contacts through counter *F*.

' Another interesting circuit[1] is a one-way recording system, which counts objects passing in one direction but not in the other.

[1] WALKER, R. C., and T. M. C. LANCE, "Photoelectric Cell Applications," Sir Isaac Pitman & Sons, Ltd.

The shadow of objects passing in front of the two phototubes obstructs first the one tube, then both of them, and finally obstructs only the second as it passes by. The power, or counting relay, has a lower resistance than the relay in the plate circuit of the amplifier connected to phototube A to which it forms a shunt circuit.

Suppose an object passes down the page, obscuring phototube A and then B. When A is shut off, plate current flows through its amplifier opening the contacts of relay X. Then as both tubes are obscured by the passing object relay Y closes, but since the contacts of X are open, no current flows through the counting
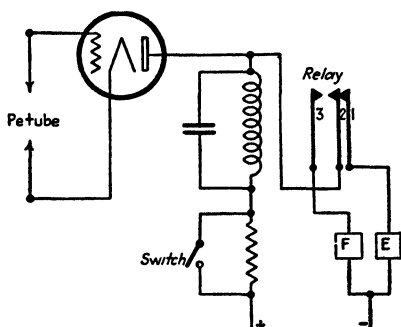
Fig. 15.—Production supervisor. *(From Walker and Lance.)*
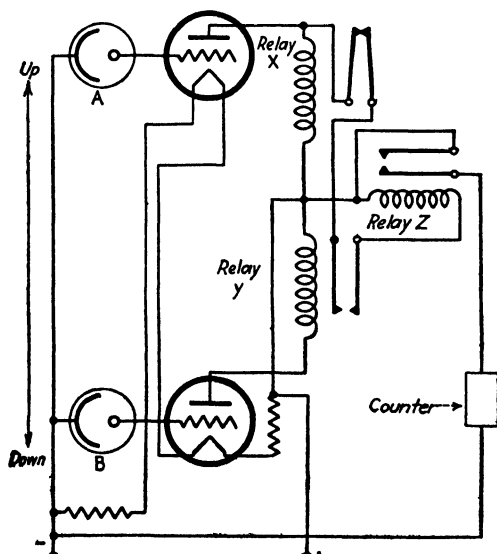
Fig. 16.—Circuit that counts objects moving in one direction but not in the other. *(Walker and Lance.)*

relay Z. As soon as the object passes by A contacts of X close but as the plate current of tube X is zero, relay Z does not

operate. As soon as the object passes by tube *B*, relay *Y* opens its contacts. Therefore in the down direction objects will not be counted.

Now suppose the object passes up the page. Relay *Y* closes because current flows through the amplifier connected with tube *B*. Then both tubes are obscured. Most of the current through the anode circuit of amplifier associated with phototube *A*

Fig. 17.—Circuit for unidirectional phototube counter.

passes through the contacts of relay *X* through the counter instead of through the coil of relay *X* whose contacts therefore remain closed. Current operates the counter. After the lower and upper tubes are again illuminated the circuit conditions are restored.

Another unidirectional counter is shown in Fig. 17 taken from the General Electric "Electron Tube Experiment Book." Two light beams shining into two phototubes are placed so that they

are parallel and no farther apart than the width of the object to be counted. Thus in a theater entrance the beams should be 3 in. or so apart. The adjustments for proper operation are made by R_7 and R_8.

Photoelectric Relays.—A combination of a photocell and amplifier has come to be known as a photoelectric relay. It is an electrical relay whose impulse comes from a beam of light which is interrupted, or turned on. The several circuits are fundamentally the same. In one case the change in illumination produces an increase in the amplifier plate current with the result that a relay closes. In the other case, the change in illumination produces a decrease in amplifier current with the result that a closed relay opens and releases a circuit from operation. The latter case is sometimes called the "reverse circuit" and would be used on a punch press, for example, where the beam of light shining across the plate permits the press to operate but when cut off, as by the operator's hand, opens the circuit between the motor and the power line.
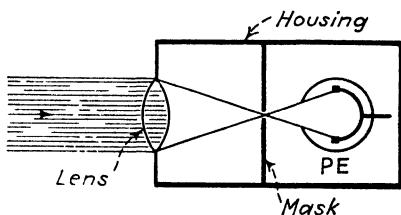
Fig. 18.—Protection for phototube from stray light.

There are three general types of photoelectric relays. There is an "outside" type, placed outdoors in a weatherproof case with lens and visor for snow, ice, and sun protection. There are indoor types with the lens and phototube in the case with the amplifier; and the third type where the phototube may be separated from the rest of the equipment by a few feet of cable. Lens types, in general, use a mask or diaphragm at the focal point of the lens, as shown in Fig. 18. This shields the phototube from all light except that which falls on the lens perpendicular to the plane of the lens, making the device directional and minimizing the effect of extraneous light.

A relay in which the phototube may be placed at some distance from the associated apparatus is shown in Fig. 19. This General Electric apparatus requires a minimum of 3 foot-candles to cause the relay to pick up equivalent to a 60-watt inside frosted Mazda lamp at 4 ft. Whatever the light available to cause the relay to close, it must be decreased by 40 per cent or more to cause

it to drop out. It will operate from light flashes of not less than $\frac{1}{10}$ sec. duration with not less than $\frac{1}{10}$ sec. delay between impulses.

In this circuit the grid of the amplifier is negative on both half cycles of the a.c. wave unless the phototube is illuminated.
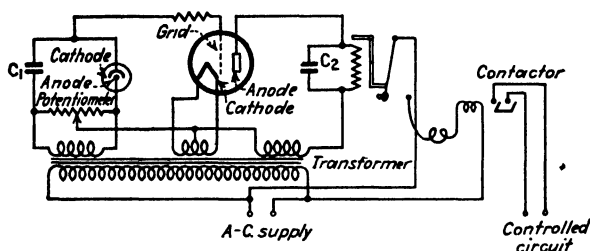
Fig. 19.—Photo-electric relay diagram.

The General Electric J-type relay (Fig. 21) uses a grid-controlled rectifier (FG-17), amplifier (57), and phototube (PJ-23). A capacity-coupled circuit makes this device sensitive to current changes, *i.e.*, to the rate at which the illumination changes. Thus
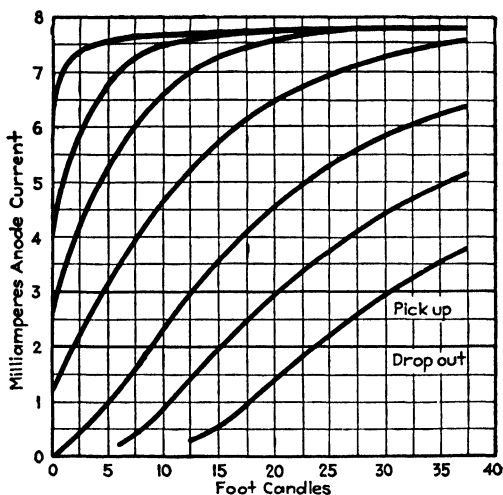
Fig. 20.—Characteristics of circuit of Fig. 19.

slow changes will not affect it, but it will respond to rapid changes. It will operate on light changes as short as 0.0001 sec. The controlled rectifier, however, passes current long enough to operate a magnetic device.

High-speed Relay.—The circuit of a high-speed light relay is given in Fig. 22, employing a double-grid controlled rectifier in place of a high-vacuum tube and relay. The power for the
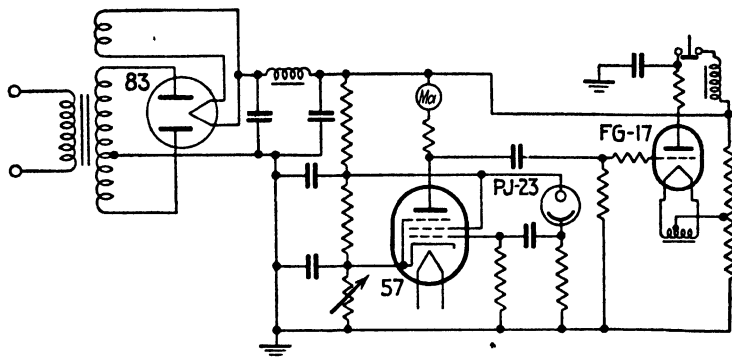
FIG. 21.—A. c. phototube grid-controlled rectifier circuit.

load circuit may be obtained directly from the tube anode circuit, or a mechanical relay may be employed, depending upon whether the tube will handle the desired power.

This circuit operates down to about 1 foot-candle; the tube passes current when the illumination is decreased.

Phototube and Controlled-rectifier Relays.—The Photo-troller (Westinghouse) is one of several units available which uses a grid-controlled rectifier instead of an amplifier because of the greater power-handling ability of this type of tube. It can be operated successfully 20 in. from a 40-watt lamp or 32 in. from a 100-watt lamp. The contacts will handle 20 amp. at 110 volts, 15 amp. at 220 volts, or if connected in series will control 30 amp. at 110 volts. The unit is a.c. operated.[1]
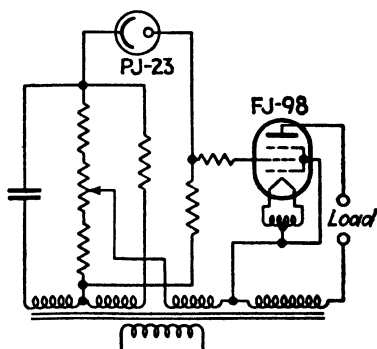
FIG. 22.—High-speed photo-electric relay.

[1] Type RK Phototroller, introduced in 1934, operates on 3 foot-candles up to 10 ft.; on one-half foot-candle with a pick-up lens and with standard light sources it will cover a throw of 50 ft. Speeds of operation up to 300 per minute are obtained.

Compensating for Residual Illumination.—It is always desirable to reduce the residual or base illumination to the lowest possible point. To this end the phototube is often placed in a cylinder which is aimed at the light source. In addition, a lens concentrates the beam that enters the cylinder and keeps out light entering the lens at an oblique small angle. An adjustment on the amplifier which varies the steady fixed bias on the tube may be made to balance out the plate current produced by the residual illumination. But in this case greater currents must come from the phototube to overcome this bias and produce in
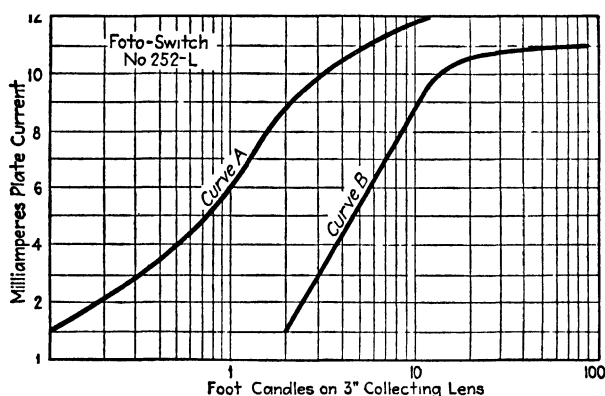
Fig. 23.—Effect on sensitivity of operating light relay in place of considerable residual illumination.

the plate circuit of the amplifier sufficient differential of plate current to operate the relay.

Figure 23 shows the effect of residual illumination on a G-M Foto-Switch. Curve *A* is for zero base illumination; curve *B* is for a base illumination of 2 foot-candles. Obviously the apparatus is more sensitive at lower value of steady illumination. Thus 1 foot-candle produces a plate current of 6 ma. at zero base illumination; six times this illumination is necessary when the base illumination is 2 foot-candles.

Power Consumed and Controlled by Light Relays.—The table following gives an idea of the power data on characteristic light relays. This table is not complete; it represents, however, typical apparatus on the market. The relay in the light relay itself may control power directly of the order shown, or by means of another relay control practically any amount of power.

DATA ON LIGHT RELAYS

Type	Manufac- turer	Min. foot- candles to operate	Power con- sumed, watts	Power controlled	
				D.c.	A.c.
CR7505-A5 ..	G.E.	3	30	10 amp. @ 115 volts	15 amp. @ 220 v.
CR7505-P1B.	G E.	0 1	30	0 5 amp. @ 115	10 amp. @ 220 v.
LE .	W.E. & M.	30	40	3 amp. @ 115	20 amp. @ 115 v.
1-A . ..	W.E. & M	15 cp at 25 ft.			
Phototroller	W.E. & M.	14 -20			30 amp. @ 110 v.
					20 amp. @ 120 v.

A Simple Photo Relay.[1]—Figure 24 shows a simple two-stage photo-amplifier relay circuit operating directly on the a.c. line.
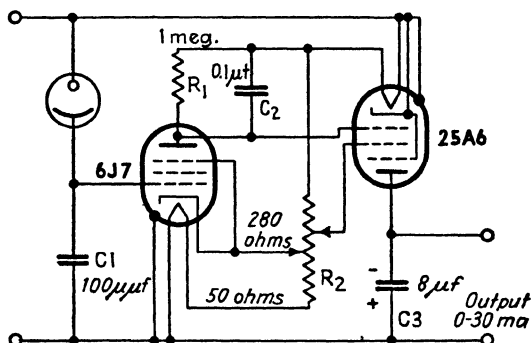
Fig. 24.—A. c. operated photo-electric relay.

The simplicity of the circuit is illustrated by the fact that the complete list of circuit parts includes only one voltage-divider resistor, one plate-load resistor, and three condensers. The circuit consists of a high-impedance phototube feeding through a voltage amplifier or buffer stage (6J7) into a power-output stage. The filament voltage of the 6J7 has been reduced to reduce the temperature of and hence the electron emission from the grid. The plate current of the 6J7 is kept at a minimum to reduce the electron bombardment of the gas molecules within the tube and hence the gas current to the grid. The bias to the grid of the buffer stage is obtained by means of the rectifying

[1] SHEPARD, F. H., I. R. E. Convention, Cleveland, May, 1936; *Electronics*, June, 1936.

action of the grid itself. This method of obtaining the grid bias keeps the effective bias or plate current of the tube constant regardless of large fluctuations in contact potential between the grid and the cathode. The impedance of the condenser C_1 acts as a load impedance for the phototube; *i.e.*, condenser C_1, as just explained, is charged up to a definite negative potential on one-half of the a.c. cycle and is allowed to discharge through the phototube on the other half of the cycle. The amount that is discharged by the phototube determines the working potential on the grid of the buffer stage. The size of C_1 can be set to any desired value to control the desired sensitivity range of the relay.

As the 6J7 conducts on only one-half of the a.c. cycle, it acts as a rectifier, and so a negative d.c. potential is built up on its plate; this negative d.c. potential is suitable for use as bias and signal for the output stage. The plate of the 6J7 is returned through its load to a point on the voltage divider (one side of the heater of the 25A6), so that it will not be necessary for the 6J7 to be cut off to obtain a zero working bias on the grid of the 25A6 output tube. This allows the 6J7 to be operated about the center of its characteristic. As the output of the 6J7 buffer stage has relatively low impedance, it is suitable for driving the grid of the 25A6 power-output stage, which in turn is capable of handling relatively large amounts of power to operate a relay.

This circuit finds its principal use in applications where relatively small amounts of light are available and where light variations last not less than one-tenth of a second.

Sensitive Light Relay.—A sensitive light-relay circuit has been proposed,[1] a pentode and a voltage-doubler tube being used with the addition of a duplex-diode high-mu triode tube and its associated circuit. The grid of the high-mu triode is actuated by a phototube connected to A,B to have the contactor pick up with incident light or to B,C to have the contactor drop out with incident light. One feature of the circuit is the addition of the double diode which rectifies voltage for the triode grid and the phototube circuit. Hence, the circuit may be described as one that triples the voltage, because from a 115-volt secondary over 400 volts of direct current is obtained. The 1-to-1 trans-

[1] LENEHAN, B. E., Meter Engineering Department, Westinghouse Electric and Manufacturing Company, Newark, N. J.

former permits the desired grounding of the cathode of the triode tube, while the tapped primary allows matching to line voltage. A useful feature is the switch 1,2 in the cathode-grid circuit of the triode, which facilitates setting. The potentiometer is turned until the light just permits operation; then the switch is thrown, giving an adequate safety factor for normal line-voltage variations.

Photometric Units.—In designing and applying light-sensitive apparatus some knowledge must be had of the photometric
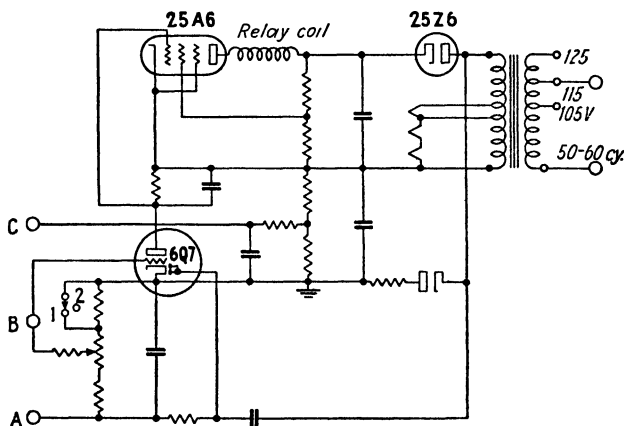
Fig. 25.—Sensitive relay circuit effecting a threefold voltage increase from 110-volt a. c. line.

units. Photocells are usually rated, as to their sensitivity, as so many *microamperes per lumen*, indicating that a light flux equivalent to one lumen will produce so many microamperes of current.

The principal terms used in engineering photo-electric equipment are the *lumen*, the *candle power* and the *foot-candle*.

Consider an *international candle*—an arbitrary chosen standard source of light. It is a source of 1 cp. Two candles will have a light emitting power of two candles. And so on. Incandescent lamps at one time were rated in candle power, but are now usually rated in the watts consumed in heating them. Automobile headlights, however, which are often used in phototube applications are rated in candle power, thus a certain bulb is a "candle power" source of light.

The *foot-candle* is the unit of illumination. A source of 1 cp. will produce one foot-candle of illumination on a surface 1 ft. from the source, and at right angles to the source. The illumination on this surface varies inversely as the square of the distance; thus at a distance of 2 ft. the illumination will be $\frac{1}{4}$ foot-candle.

The *lumen* is the unit of light flux. In photo-electric tubes a given current is produced by the cathode absorbing a certain number of lumens of light; in thermionics a cathode emits so much current per watt of heating current absorbed. The lumen is the *total flux received by a unit area at a unit distance from a unit source.* Thus a surface of 1 sq. ft. which receives an illumination of 1 foot-candle is stated to receive a flux of one lumen.

As an example of the use of these units suppose a 10-cp. lamp is 2 ft. from a photocell whose opening to the sensitive surface is 0.9 sq. in. It has a sensitivity of 15 μa per lumen. How much current will flow? A source of 10 cp. will produce 10 foot-candles at 1 ft.; at 2 ft. it will produce one-fourth of this value or 2.5 foot-candles. If this illuminates a surface with an area of 1 sq. ft. the light flux will be 2.5 lumens. The photocell, however, has an area of only 0.9 sq. in. The light flux on 1 sq. in. of surface will be $\frac{1}{144}$ of the flux on 1 sq. ft. and therefore $2.5 \div 144 \times 0.9$, or 0.0156 lumen will be the flux into the opening of the photocell.

Since the sensitivity of the tube is 15 μa per lumen, the current flow will be 15×0.0156, or 0.234 μa. If this current flows through a 10-megohm resistance, the voltage drop across this resistance will be 2.34 volts.

Thus *to get flux in lumens, multiply the area of the surface (in square feet) by the illumination in foot-candles. To get foot-candles divide the candle power by the square of the distance (in feet).*

Light Intensities Found in Practice.—The illumination in direct sunlight may amount to as much as 10,000 foot-candles. In the average home the illumination is of the order of 2 to 5 foot-candles; in an office between 3 and 10 foot-candles. Good illumination requires approximately 15 foot-candles.

According to Langmuir and Westendorp[1] with a photocell and amplifier, which are much more sensitive to diffused light than the eye, an absolute brightness change of only 4×10^{-11} candle per square centimeter can be detected or about one-sixth the threshold of the eye's sensitivity. The photocell-amplifier

[1] *Phys.*, November, 1931.

system requires 2.5 candles at 1 km. for operation. In full moonlight, the photocell can detect a diffuse modulated light of an intensity of only 1/13,000 of that of a diffuse flashing light just visible to the eye. In clear air at a distance of 11 km. a light of 0.11 candle is visible with a completely dark background, 0.85 candle with starlight, 5 candles with moonlight, 85 candles with twilight (stars just visible) and 8,500 candles in daylight.
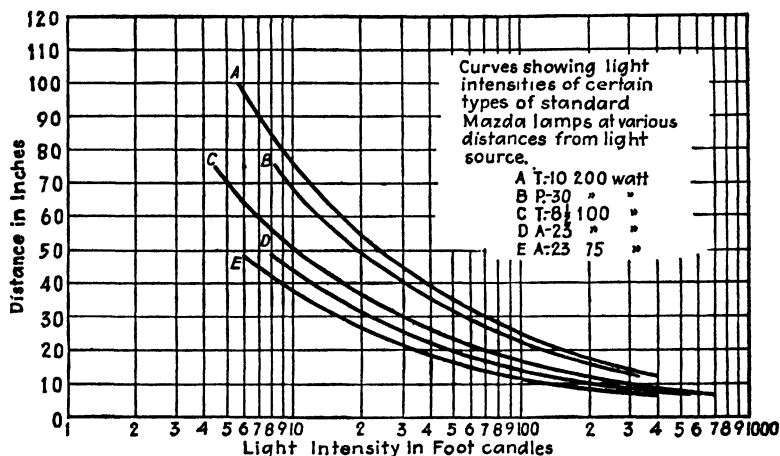
FIG. 26.—Illumination at various distances from Mazda lamps.

Methods of Determination of the Intensity of a Light Source.— It is necessary to know the luminous intensity of a light source in order to specify the circuit constants for phototube operation. This information can be obtained in the following ways:

1. Direct photometric measurement.
2. Comparison with a standard lamp by use of a phototube.
3. Comparison with a Mazda C lamp by use of a phototube. Mazda C lamps of 50 to 100 watts are rated at approximately 1.0 cp. per watt at normal voltage (this method is accurate to 10 to 20 per cent only).

When the candle power is known, the amount of light flux in lumens upon a given area is calculated as follows:

$$L = \frac{cp. \times area}{(distance)^2},$$

area and distance being in corresponding units. This method

assumes a point source and area measured perpendicular to direction of light flux.

Effect of Lamp Temperature.—It will be noted carefully that the spectral characteristics of an incandescent lamp vary appreciably with the temperature of the lamp. Therefore some fixed temperature must be used·in measuring the sensitivity of light-sensitive cells. A tungsten filament with a color temperature of 2870°K. is recommended by the Institute of Radio Engineers. It is possible to approximately double the rated sensitivity of certain phototubes by using a lower temperature in the filament of the measuring lamp.
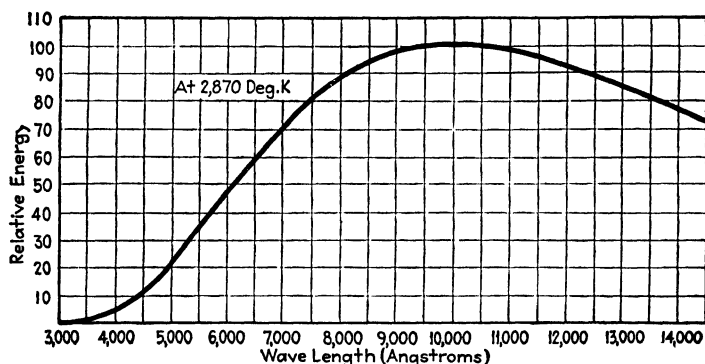
Fig. 27.—Radiation from incandescent lamp.

Light Sources.—In the average industrial use an artificial light source properly focused upon the phototube is to be preferred to daylight or general illumination. It is desirable to keep down the extraneous, or base, illumination to a minimum so that the phototube may have no difficulty in determining when the light supply has been cut off. It is desirable that the person or object that obstructs the light should do it completely, thereby providing the greatest possible change in illumination so that the greatest possible current change through the relay may result.

Automobile headlight lamps have been widely used with a lens to concentrate the beam into a narrow ray and to direct it upon the sensitive surface. The table below is taken from *Westinghouse Bulletin* describing light sources and light relays. It shows the distances from the light source at which several relays may be operated.

Light relay	Min. foot-candle at window	Light source, feet			Incandescent lamp, inches	
		B 21 cp.	B 32 cp.	C 32 cp.	50 watts	100 watts
LC with SR-50 tube	20	14	18	5	11	17
LC with SK-60 tube	10	21	25	7	17	25
LD with SR-50 tube	10	21	25	7	17	25
LD with SK-60 tube	5	29	35	10	23	34

In laying out an installation it is necessary to survey the proposition to learn the actual distance the light must traverse, the condition of base illumination which will not be affected by the light beam being interrupted, and then the light relay and light source must be properly chosen with these conditions in mind.
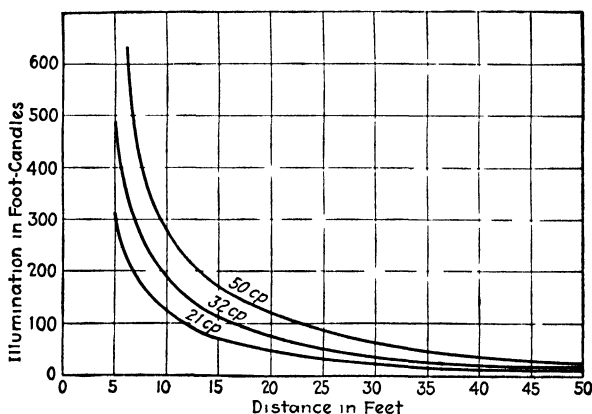
FIG. 28.—Light characteristics of automobile headlamps.

To conserve the life of the light source it is common practice to operate it slightly under rating. The table below taken from

Percentage voltage	Percentage cp.	Percentage watts	Percentage life
90	68	84	430
95	83	92	205
100	100	100	100
105	118	107	52
110	140	116	26

G-M Laboratories bulletin on photo-electric relays shows the effect of such operation of a typical automobile headlight designed to operate on a 6- to 8-volt source.   Since this particular lamp
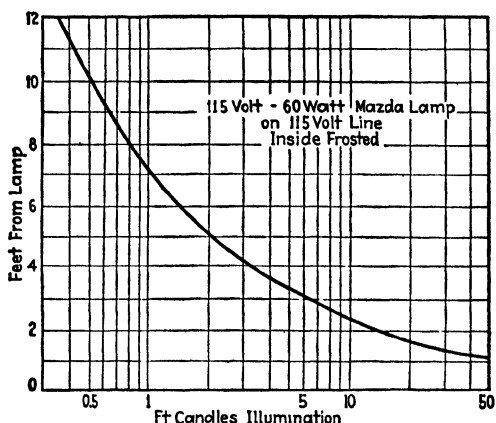
FIG. 29.—Foot-candles *vs.* distance for typical lamps.

had a life of 100 hours operated at the proper voltage, a life of over 400 hours could be obtained by operating it at 90 per cent of this voltage at a loss of 32 per cent of its maximum light.

Westinghouse (1934) has a Type E light source which delivers 24 foot-candles at a distance of 25 ft. useful in steel mills or places where dust, steam, etc., must be penetrated. The lamp is a 6-volt, 5-amp. bulb with a life of 3,000 hr.   A lens is used to concentrate the beam.
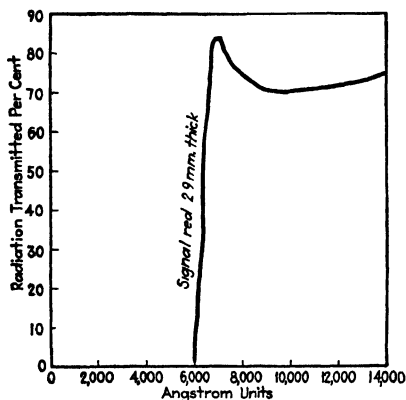
FIG. 30.—Transmission characteristic of red filter.   (*After Walker and Lance.*)

Control by Invisible Light. It is often desirable to control the light relay by means of invisible light such as is emitted from a source of infra-red.   This light may be obtained by placing a deep-red filter over the source of light.   The curve[1] in Fig. 30 gives the characteristics of such a filter obtainable in England.   Since

[1] WALKER and LANCE, see Bibliography.

the average limit of visibility for individuals is about 6,500 angstroms, it is only necessary to cut off about this point. The incandescent lamp or automobile headlight has considerable radiation in the region of wave lengths longer than this and therefore makes a suitable source.

It must be remembered that such filters reduce materially the illumination at the distant phototube. This reduction may amount to as much as 75 per cent of the original intensity leaving only 25 per cent to affect the lamp.

Red filters are made by the photographic manufacturers, and other sources are able to supply them in the United States (Fish-Schurman, New York, for example, handle Jena filters). RG-9 is a good example of glass cutting out nearly all the visible red. Another is Corning Glass Works Sextant Red glass which removes the visible. Still another is Wratten No. 87 or Corning No. 254. Corning Aklo glass removes infra-red.

Filters for Ultra-violet Region.—When it is desired to utilize the ultra-violet region or to measure a limited portion of the ultra-violet spectrum,[1] one encounters the embarrassment of choosing proper filters to exclude all radiations not of interest and to transmit these radiations in which interest is centered. For example, if radiations of the erythema region (2800 to 3200 Å.) are to be measured, a first approximation may be had by using a caesium-oxide cathode in Corex D in addition to a filter such as Corning Red-purple Corex 986. A second approximation results from the addition of a liquid filter consisting of a nickel sulphate solution. Ultra-violet response is limited by the combination to the region 2600 to 3700 Å., but unfortunately both the Corex 986 and the nickel sulphate are transparent to infrared light between 8000 and 9000 Å.—light to which the caesium oxide surface is notably sensitive.

If a caesium oxide surface in a Corex-D envelope is exposed alternately through Corex-D and lime-glass filters to general radiation, the variable component of the tube response will be a measure of the intensity in the erythema region. By suitable choice of glass for the envelope and filters, any spectral region may be similarly isolated and measured. The filters may in practice appear as alternate sectors of a disk rotated with proper frequency in front of the tube. An inherent difficulty of applica-

[1] WILSON, E. D., Electrochemical Society, Cincinnati, Apr. 23–26, 1936.

tion of this principle, particularly when the energy of the region to be measured is small compared to the total energy of the incident light, is the same as that always encountered in any attempt to detect a small difference between two large quantities. For example, it may be difficult to prevent saturation in the input circuit of an associated amplifier; or, in obviating saturation, instability may be introduced. However, the method is feasible and should prove useful in many cases.

A more elegant method for measuring isolated regions in the ultra-violet is provided through the use of special ultra-violet phototubes developed by Rentschler, Henry, and Smith[1] of the Westinghouse Lamp Company. These tubes consist of pure sputtered films of various metals enclosed in envelopes of Corex glass or quartz. Although their current sensitivity is relatively low, they have the distinct advantage of having their total response confined to quite narrow spectral regions of the ultra-violet, being entirely insensitive to any other light. The long-wave limit is defined by the threshold frequency of the particular metal involved, while the short-wave limit is fixed by the absorption characteristic of the envelope.

Reflector versus Lens Type of Light Sources.—In many cases it has been possible, or desirable, to use a reflector instead of the lens system. For example (G-M Laboratories), the light source and the phototube can be in the same housing, the beam being projected across a space to mirror and reflected back into the phototube. In general, the lens is used where a more constant output is desired, where the beam must be of small diameter, and where the maximum obtainable collection of light is not necessary. The lens is simpler to clean than a polished mirror. The latter, however, will collect more light (about 180 deg. solid angle) than a lens which cannot do much better than collect 60 to 70 deg. solid angle. Where a large beam may be used, where constancy of light value is not so important, and where the greatest amount of light must be had, the reflector is used. In using mirrors a loss of illumination is suffered. At each reflection it is probable that the loss is at least 40 per cent and with two reflections the resultant light intensity would be only 0.60 × 0.60, or 36 per cent.

[1] RENTSCHLER *et al.*, *R. S. I.*, 3, 794, 1932.

At times the beam of light must be passed through a pane of glass, for example, into a store window. If a considerable angle exists between the incident beam and a line perpendicular to the pane, an appreciable fraction of the light will be lost.

Planning a Phototube Installation.—When ordering an installation from a manufacturer, or designing one for use, the following questions should be answered. They have been prepared by R. C. Hitchcock of Westinghouse.

A. Light Beam:

    1. Will ordinary visible (incandescent white) light be used?
Or must the light be practically invisible (infrared)?

    2. Is the light beam to be horizontal?
Or what angle is it from the horizontal?

    3. Will the beam be sent directly from source to phototube?
Or how many mirrors are to be used?

    4. What is the total length of the light beam?

    5. How large is the object (length, width, and height) that intercepts the beam?
Or what is the aperture size through which the beam must pass?

    6. How far from the light source is the intercepting object?

B. Phototube:

    1. Is the phototube to be inside the relay housing?
Or, if separately mounted, how far is it from relay?

    2. Can sunlight, reflected sunlight, or strong artificial light enter the phototube housing?

C. Air:

    1. What is the room-temperature range?

    2. Will the relay be installed where excessive dampness exists?

    3. Will the housings be exposed to direct heat from the sun, etc.?

    4. Is equipment to be used outdoors?
If so, in what direction (approximate) will the beam be sent from source tc phototube (*e.g.*, from southwest to northeast)?

D. Contactor:

    1. How many complete operations are desired per minute?

    2. Give the characteristics of the circuit to be opened (volts, amperes, frequency).

    3. Is the load highly inductive?

    4. Is contactor to be closed (or open) with light on phototube?

    5. What is the minimum duration of complete light change for which relay operation is desired?

E. Mounting:

    1. Is there a limit on the size of the housing?

    2. Will the phototube and light-source housings (and mirrors, if any) be readily accessible for cleaning optical surfaces?

    3. Will mounting be from wall? Floor? Ceiling?

F. Power:
  1. Line voltage (actual maximum and minimum, if possible).
  2. Frequency (if alternating current) cycles per second.
  3. Is the line solidly grounded?
  4. If relay is to be used 24 hr. a day, what is the night voltage range?
G. Service:
  1. Approximately how many hours a day is relay to be used?
  2. How many days a week?
  3. What is the general nature of the proposed application?
      a. Protection.
      b. Safety.
      c. Supervision.
      d. Control.
      e. Counting.
      f. Door operating.

Applications of Light-sensitive Tubes.—The following applications have been actually made and are in practice. Recitation here cannot hope to include all such circuits or uses, but it is hoped they will serve to show the manner in which phototubes have come to serve industries other than those closely connected with communication. As already pointed out, some applications require linearity between light and current output; others depend upon the color sensitivity of the particular cell used; and in many others all that is necessary is a momentary or permanent interruption of a source of light which sets in motion, almost instantaneously, a train of events as complicated as the engineer can devise.

Jigsaw Puzzle Rejector.—A method typical of the use of light-sensitive equipment for automatic inspection and rejection is illustrated in Fig. 31. It is to insure that all the pieces of the puzzle get into the box which the purchaser buys. As described by Nicholas Heyman in *Electronics* the operation is as follows. A puzzle is fed under the hood, and when in position the light source is turned on. If all pieces are present (the puzzle has been cut but not broken apart) the puzzle is passed on to the breaker-conveyor belt. But if a piece is missing, light will get through to the phototube which through an amplifier will operate a solenoid, drop the shelf on which the puzzle passes, and dump the pieces into a container.

The device performed perfectly at 40 puzzles per minute, even though there were 300 or more pieces to the design.

An Automatic Race Timer.—Foot races are usually timed by a practiced observer standing at the finish line who starts a stop watch when he sees the smoke from the gun at the starting line, and then stops the watch as the runner crosses the tape.   That
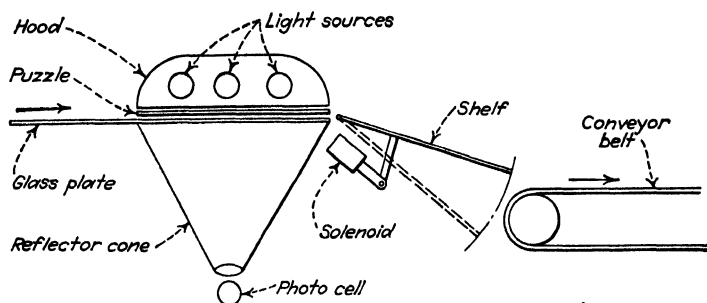
Fig. 31.—Jigsaw puzzle inspection set-up.
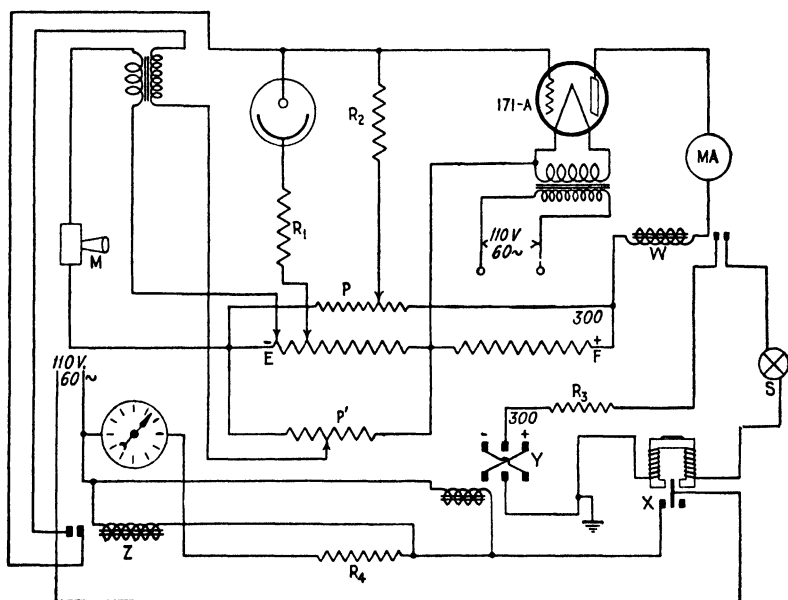
Fig. 32.—Automatic race-timing circuit.

there must be considerable error in this system is shown by the work of psychologists who have investigated reaction times. Their results range from 0.175 to 0.225 sec. for the time between reception of an optical stimulus and the physical action which

follows recognition of that stimulus. This time is never found to be less than 0.16 sec. and that is generally considered to be the minimum delay which is not reducible by practice. It is bad enough that such a large quantity which must vary between different observers should enter into the timing; but there is another source of error in that the delay is not the same for the start as for the finish because the timer sees the runner approaching the tape and can anticipate the moment when his chest will touch it. All racing times recorded by this method are therefore subject to uncertainties which depend on human reaction times and are probably from 0.1 to 0.2 sec. too short.

The circuit shown times races accurately to 0.01 sec. and its timings have been recognized by the I.C.A.A.A.A., the official American body for intercollegiate track records. A description of the operation of the circuit will be found in the author's paper.[1]

Partridge[2] has described a method of using a microphone, light-sensitive cells and a phonograph turntable to make permanent records in ink on a circle of paper. The accuracy of the timing of the event is 0.001 sec.

Partridge states that the method may be used for viscosity measurements, recording occasional arrivals of radiation in an ionization chamber, measuring velocities and accelerations of electric motors under varying input and load conditions, for velocity and acceleration of automobiles, airplanes, hydroplanes, and the like with different loads and fuels, deceleration with braking, etc.

Selenium Speed and Acceleration Recorder.—A method of recording in ink on a revolving disk the time when a runner, for example, passes various points in his course has been developed by Partridge.[3] The device is capable of directly recording in ink fourteen or more successively occurring events to 0.001 sec. with an accuracy equalling that of the 60-cycle power frequency. (In New York the frequency is maintained at 60.00 ± 0.03, representing an accuracy of one part in two thousand.)

[1] SPEAKMAN, E. A., *Rev. Sci. Instruments*, vol. 2, No. 5, pp. 293–296, 1931. See also LADD and WOODWORTH, "Elements of Physiological Psychology."

[2] PARTRIDGE, H. M., *Electronics*, p. 262, August, 1932. See also FETTER, C. H., and H. M. STOLLER, Precise Timing of Sporting Events, *Elec. Eng.*, June, 1933.

[3] *Electronics*, August, 1932.

A microphone is placed over the runner's head to pick up the starting gun. Brass plates are provided for the hands of the runner and a record is made on the disk when the gun is fired, when the runner's hands leave the starting plates (0.1 to 0.25 sec. later) and by means of several selenium cells placed at intervals along the track when the runner passes these points. Each time the runner intercepts the beam illuminating one of the cells the amplifier associated with the group of cells operates a relay which in turn actuates a Taylor reservoir-type recording pen which is traveling diametrically toward the center of a synchronously revolving disk. Sixteen-inch disks are used; one revolution is equivalent to 0.750 sec. A 0.05-hp. induction motor drives the pen toward the center of the disk at such a rate that the normal distance between lines is 0.125 in. When the pen gets an impulse from the light-sensitive cell, a sharp V is put in the record. Time is reckoned between these nicks by the angular rotation of the disk.

The timing mechanism is in operation at the start and end of the race; each stimulus is subject to the same delays.

The "Electric Eye."—The photocell is often referred to as the "electric eye," but as L. R. Koller has pointed out, the analogy must not be carried too far. A few of the light-sensitive surfaces used, notably the dry-type photo-voltaic cells have responses similar to that of the human eye. In general, phototubes do not "see" as the eye sees. A comparison of the relative sensitivities of the eye and the phototube shows the latter, plus the amplifier, to be about 20 times as sensitive as the eye. The dimmest star which can be seen by the eye (sixth magnitude) delivers about 5.5×10^{-13} lumen to the unaided eye.

With the best phototube available this will produce about 1.1×10^{-16} amp. of current; the best amplifier (the FP-54) will detect 0.5×10^{-18} amp. But with all its variables such as the wave length of light, the voltage, the intensity of the light, etc., the phototube makes only a single manifestation, a change in current. Only the eye creates an image, unless one can speak of the Zworykin television tube, the iconoscope, and the Farnsworth image dissector types of tubes as creating images.

Smoke-density Recorder.—Several photo-electric recording meters have been devised as a means of indicating proper combustion and many installations made. These meters utilize a

beam of light projected through the smoke stack and either permitted to enter a photocell on the opposite wall or reflected back through the stack to enter the photocell aperture after passing twice through the smoke. A continuous record may be made and an alarm rung when the smoke becomes too dense indicating bad combustion.

The recording instrument may be calibrated according to the Ringlemann chart.[1] Samples of such recordings are found in
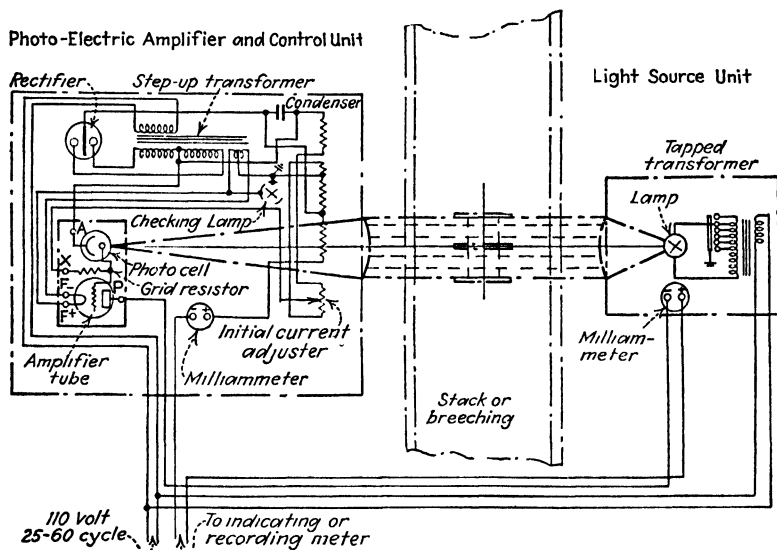
Fig. 33.—Smoke indicating or recording systems.

Fig. 34. Periods when the grates were cleaned, or when the load began to pick up are clearly shown. With such apparatus it has been found that firemen or plant operators were able to keep the smoke down to about 0.5 density day or night compared to No. 3 density at night or at other times when bad fluctuations occurred.

Smoke-alarm Relay.—Weston engineers have developed an ingenious device which warns when improper combustion takes place and continues to ring an alarm intermittently until the condition is corrected. The usual light source shining through the stack into a light-sensitive unit (Photronic cell) is employed. The light source is a 21- or 32-candle-power automobile head-

[1] VEDDER, E. H., *Elec. J.*, May, 1929, p. 199.

lamp, and to take care of stacks of different diameters a trans-
former with rheostat is provided.   For a stack 8 to 10 ft. in
diameter the lamp would operate at about $4\frac{1}{2}$ volts with an
average life of about one year.

On the relay panel is a contact-making indicator that is cali-
brated directly in smoke units.   Number 2 smoke is the value
at which black smoke appears and the contactor is adjusted so
that at No. 2 smoke the contact is made.   If it is desired to have
the equipment operate at any value other than No. 2, this may
be accomplished by adjusting the pointer position by means of the
screw on the front of the indicator.
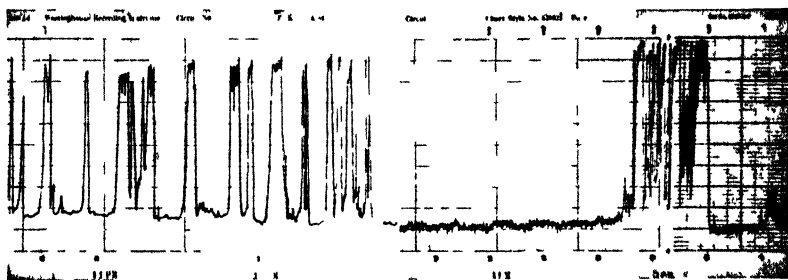
FIG. 34.—Samples of charts obtained with (right) photo-electric smoke density
control   Variations without control are shown at left.

When the relay makes contact, the small induction motor is
started which rocks the mercury tube and causes it to make
contact and sound the alarm.   The alarm will sound for a period
of about 30 sec. and during that time the contactor is pushed
away from its contact so that if the operator corrects the smoke
condition the alarm will stop.   However, if the smoke condition
is not corrected, the alarm will be off for a period of about 30
sec. and then will repeat until this condition is taken care of.

The relay panel may be mounted at any distance from the
light collector, provided the leads do not have a resistance greater
than 100 ohms.   The relay or contact-making indicator is pro-
vided with a magnetic pull-in on its contacts so that vibration
will not cause a "sputtering" of the contacts, and a long life on
the contacts is assured.   The control panel is mounted in a dust-
proof conduit box with a glass window in front of the indicator
so that the readings may be observed by the boiler room operator.

In case a recorder is required to show how long the smoke
has exceeded the value for which the alarm is set, a voltage

recorder may be connected to the mercury tube so that when the alarm sounds the recorder will draw a line at the normal voltage point as long as the alarm sounds, thus giving a record of the period during which improper combustion occurred.

Illumination Control.—A rather obvious application of phototubes is the control of illumination according to daylight conditions. Turning on and off electric signs, floodlights, etc., by means of such systems has proved to be not only money-saving but attention-getting systems as well. It is as absurd to operate
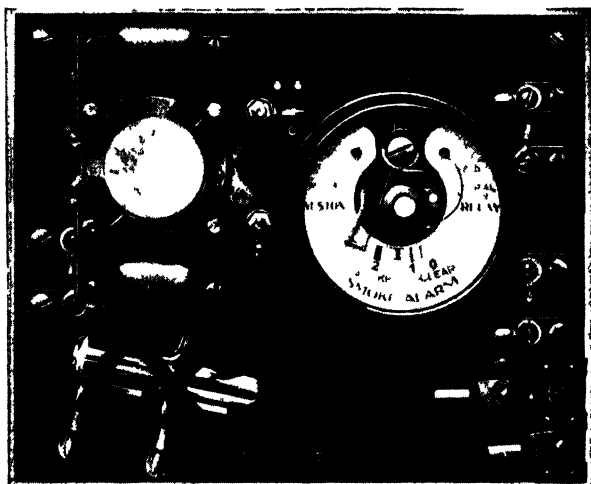
Fig 35.—Weston unit giving alarm of incorrect combustion

a large sign during daylight hours, as it is not to have it turned on during periods of temporary darkness. The illumination in school rooms, on work benches and in places where machine tools, etc., are used may be controlled by the proper equipment, resulting not only in a power saving but in better working conditions, less shrinkage from poor workmanship, etc.

Daylight varies a great deal from time to time during the day and also varies greatly during different seasons of the year. But with phototube equipment, variations in natural light can never interfere with good working illumination on any day in the year. Methods of turning lights on and off in the past have depended upon someone's judgment. Such judgment is inaccurate, because when weather conditions vary, decrease of natural illumination is so deceptive that lights are seldom turned on until

long after they are needed—then left burning when artificial light is not necessary.

It has been found that on several installations in which interior factory lighting was controlled, it was possible to increase the illumination by installing twice the existing wattage of lamps with no increase in power consumed. Thus, the phototube installed in factories, offices, and schools, removes the handicap of darkness in the first half of its operating cycle and, in the second half, saves the cost of unnecessary lighting.

To obtain the maximum advertising value from signs and show windows, it is essential that they be illuminated whenever artificial lighting can increase their visibility. Often, during the winter, signs and show windows cannot be seen even in daytime, due to fog and smoke prevailing in most large cities. This prenatural twilight period is usually about 5 o'clock in the afternoon when many people pass the signs and show windows. Since it is important to have signs and show windows attract attention at this time, the photo-electric equipment performs a real service by turning these lights on and off as needed.

An ingenious use of a photo-switch was made by Teletouch Corporation (New York City) and R. H. Macy's department store in August of 1936. At night the windows of this large store are dark. A beam of light projected through a window to the sidewalk reflects sufficient light into a phototube within the window, when anyone passes by, to light up the store window illumination. The lights stay on for a certain period, say 1 min., and then automatically go out. Macy's and Teletouch secured considerable newspaper publicity by this device and of course the wares in the window were seen by many hundreds of passersby who were intrigued by their ability to turn on the lights for a look whenever they pleased.

During early morning hours, usually from 1 to 5 o'clock, a time clock may be used to turn the lights off. Thus the phototube plus a simple time clock can be arranged to give complete automatic control of illumination.

Some of the places where this type of apparatus was applied to turn artificial light on and off at every change, without any supervision are: offices, show windows, schools, signs, flood-lighting installations, street lighting, navigation lights, and airway and airport lighting.

In a particular installation[1] a photocell relay is used to turn on and off lights on the benches of machine tool makers as the light from the sun varied. An illumination of approximately 15 foot-candles is maintained; when the value falls to 14 foot-candles, the phototube turns on artificial lights which stay on until the daylight has reached a value of 20 foot-candles.

Appreciable saving in lamps was experienced. Ordinarily about 1,200 lamps per year were used; after phototube control
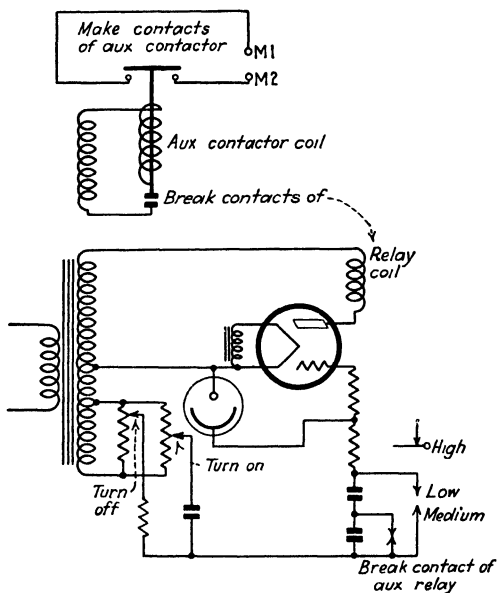
Fig. 36.—Circuit for illumination control.

was installed, the lamp requirements dropped to from 900 to 1,000 per year. Although power was purchased on a demand basis and no meter measurements were available to indicate the saving in power, it was estimated that a monthly saving of from \$35 to \$40 could be made by the automatic control of illumination.

The circuit of the installation is shown in Fig. 36. The turn-off and turn-on potentiometers are adjusted to give the desired range of control and can be fixed for any set of intensities from 6 to 150 foot-candles. The lighting circuits, 110 volts, three phases,

[1] PORTER, C. J , Saving Money with Phototube Light Control, *Elec. J.*, vol. 29, No. 11, p. 506, November, 1932.

25 cycles, are controlled by a three-pole single-throw oil circuit breaker having a capacity of 300 amp. at 2,200 volts. Six of these breakers are built into a cam-operated mechanism which permits only one circuit breaker to close at a time and all to open at once. The cam shaft is driven by a 1.5-hp. three-phase 110-volt 25-cycle standard induction motor having a speed of 715 r.p.m. through a gear reduction unit having a ratio of 25 to 1. The cam shaft has a speed of 28.6 r.p.m.

When illumination falls below the required minimum, the relay starts the motor and closes the circuit breaker. When all the
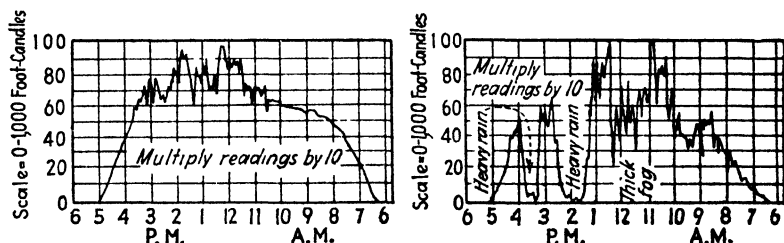
Fig. 37.   Left, north sky on clear November day   Right, north sky on foggy and rainy November day.   (*Weston*)

breakers are closed by the rotation of the cam mechanism, the circuit is automatically opened, and the motor stops.

When the light has come up to the desired value, phototube reverses the above action opening the lighting circuits and leaving the circuit and apparatus in the original condition.

Compensation for Temporary Light Fluctuations.—Although any photocell-amplifier circuit will turn on and off illumination of any sort when sunlight, for example, changes within certain arbitrary limits, modifications are necessary if the control is not actuated by passing clouds or temporary changes in illumination. The negative bias of the triode, for example, may be adjusted by means of a variable capacitor to facilitate the setting of the device for operation at a given light intensity. Small thermally operated time-delay relays are interposed between the plate relay and the position relay, making it necessary for a given change of light to be maintained for several seconds before the position relay is operated. This circuit is particularly adapted for the control of artificial illumination in accordance with day-light. It has been used for street-light and sign control. Such apparatus will automatically turn lights on and off.

A record[1] of the light from the north sky on a clear day was obtained by exposing one "photronic cell" to the north sky and connecting it directly to a standard recorder. Street lights controlled by this relay would be shut off at approximately 6:15 a.m. and turned on in the evening at approximately 5:15. The variation in illumination obtained on a rainy day is striking. At 12:17 p.m. the foot-candles measured 200, but less than 10 min. later they had increased to 1,000; at 1:40 p.m., during a heavy downpour, the illumination dropped to 8 foot-candles.

Typical Illumination Equipment.—In the Photolux (Westinghouse) an amplifier tube energizes a primary relay. The primary relay energizes the main contactor. Interposed between the relay and contactor is a time-delay button functioning on both opening and closing to give several seconds' time delay. The time delay avoids operation by someone walking in front of the unit or by lightning flashes at night.

If either the phototube or amplifier tube fails from a normal cause, the light will remain turned on, because when the primary relay is deenergized, the auxiliary contactor is in the energized position, in which position the lights being controlled are turned on.

Adjustment is provided by two dials, one to control the light intensity at which the device turns on the light, the other to control the light intensity at which the device turns off the light. The turn-off and turn-on dials operate potentiometers which control the residual grid-bias voltage of the amplifier tube. By residual grid-bias voltage is meant that voltage which would exist with the phototube dark. The turn-on potentiometer controls this residual bias voltage when the lights being controlled are off, and the turn-off potentiometer controls the residual bias voltage when the lights are on. This change of voltage control from one potentiometer to the other provides a method of modifying the natural lock-in of the primary relay, eliminates the necessity for any relay adjustments, and makes possible independent adjustment of the turn-on and turn-off operation.

[1] LAMB, A. H., *Elec. World*, Apr. 16, 1932. See also LAMB, A. H., and W. R. WEISE, *Elec. World*, Nov. 24, 1934. In *Illum. Eng.*, vol. 28, pp. 48, 94–96 February, 1935, is given a description of the Holiphane-Edgecumbe photometer, together with data concerning linearity of response, errors at various angles of incidence, sensitivity at different wave lengths, and creep and temperature variations.

All models are available with or without a synchronous time clock which is adjustable to turn the lights off after a certain hour at night and on again at a predetermined hour in the morning. The maximum period of lights off for which the clock is adjustable is 12 hours.

The equipment may be installed either indoors or outdoors if the proper unit is ordered. Vibration or shocks insufficient to be harmful to the strong type of vacuum amplifier tube employed will not affect the operation of the unit. In an average indoor installation such as a modern office, the Type RA will control the illumination between the limits of 2.5 foot-candles turn-on and 30 foot-candles turn-off as measured on a horizontal plane near the unit. The outdoor type RB will operate to turn on the lights as low as 2.5 foot-candles and turn them off as high as 20 foot-candles.

The outdoor models for very sensitive operation are equipped with copper oxide dry rectifiers which provide d.c. to a very sensitive amplifier circuit. The rectifiers and filters are mounted on the back of the main panel, while the other apparatus such as relays, tubes, transformers, etc., are mounted on the front in the same location as in the indoor models.

For relatively insensitive operation such as control of signs, a more simple form is provided.

In locating the Photolux it is not necessary to shield it from the artificial light that it is to control, unless the artificial illumination at the point chosen is more than three times the natural illumination at which the relay turns on the light—an unusual condition. The relay should be located where the illumination is fairly representative of the illumination to be controlled. The location near the main contactor by which lights are to be controlled, for convenience in wiring, is a secondary consideration.

Experience has shown that there are several considerations that satisfactorily fix, at least approximately, the selection of the turn-on and turn-off point. In the first place, the artificial lighting being controlled probably represents an estimate of the minimum acceptable illumination. It is obvious then that the artificial lights should be turned on when the daylight gets this low. Usually it is economical to turn them on before it gets to this point.

Secondly, the natural illumination corresponding to turn-off should be approximately twice that corresponding to turn-on. This usually means that the actual light intensity of the unit at turn-off will be between two and three times the light intensity at turn-on depending on how much effect the lights being controlled have on the relay. This differential is desirable to avoid annoyingly frequent operation of the unit since natural light often fluctuates quite rapidly.

The Photolux may be calibrated conveniently at night when the natural illumination is negligible. An ordinary 150-watt Mazda lamp on an extension cord can be used to provide a sub-
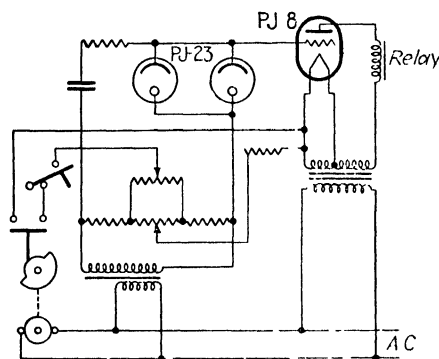
FIG. 38.— Circuit of Novalux control.

stitute for natural illumination which can be varied at will. A foot-candle meter or illuminometer is a convenient means of measuring the light intensity.

For 110-volt operation, the contacts of the auxiliary contactor in the unit are suitable for 20 amp. on alternating current or 0.5 amp. on direct current with an inductance of 7 h. or less. This rating permits operation of contactors up to and including a single-pole 600-amp. contactor.

The General Electric Novalux lighting control uses two phototubes (PJ-23) in parallel operating into an amplifier which in turn operates a relay which turns the lights on and off. The two phototubes increase the sensitivity of the apparatus to permit operation at low light intensities desired by municipalities. Thus the unit will operate with an illumination of about $\frac{1}{4}$ foot-candle on the window of the unit. The use of two phototubes

is more economical and better in other ways than the use of additional amplification required to get equivalent sensitivity.

The phototube in this unit has a life of approximately 35,000 hr., and the amplifier has an expected life of 8,000 hr. If the amplifier fails, the lights will be turned on automatically. The circuit for this system is given in Fig. 38.

The following table gives the power-handling abilities of the unit:

10	amp. @ 115 volts alternating-current	Inductive load
10	amp. @ 230 volts alternating-current	Inductive load
0.3	amp. @ 115 volts direct-current	Inductive load
0 08	amp. @ 230 volts direct-current	Inductive load
2.5	amp. @ 115 volts alternating-current	Incandescent lamp load
2.5	amp. @ 230 volts alternating-current	Incandescent lamp load

A Phototube Automatic Sorter.—A method[1] which has been used for automatic testing of resistors used in radio receivers is
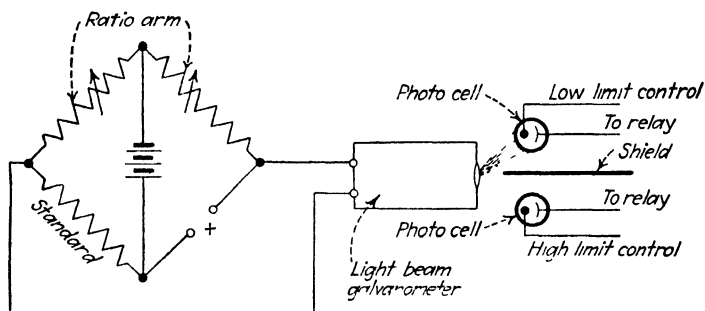
FIG. 39.   Phototube method of sorting resistors in production.

shown diagrammatically in Fig. 39. It consists of a standard bridge circuit with the positions of the battery and galvanometer reversed to allow higher voltages to be applied to the bridge to increase its sensitivity at high-resistance values without damaging the ratio arms.

The indicating device used is a light-beam type of galvanometer of the Leeds & Northrup Company, developed especially for resistor measurements. The deflection of the light beam is dependent on the degree of variation of the X from the standard resistance of the bridge. Consequently the two photocells are spaced at a distance apart which corresponds to the deflection of

[1] PODOLSKY, LEON, *Electronics*, July, 1933.

the light-beam galvanometer at the high- and low-resistance limits. The conveyor brings the units to be tested successively from a hopper to the testing station where contact is made to them. If the resistance value of the unit being tested differs from the standard, the bridge will be unbalanced and the light galvanometer will deflect right or left according to whether the X unit is higher or lower than the standard.
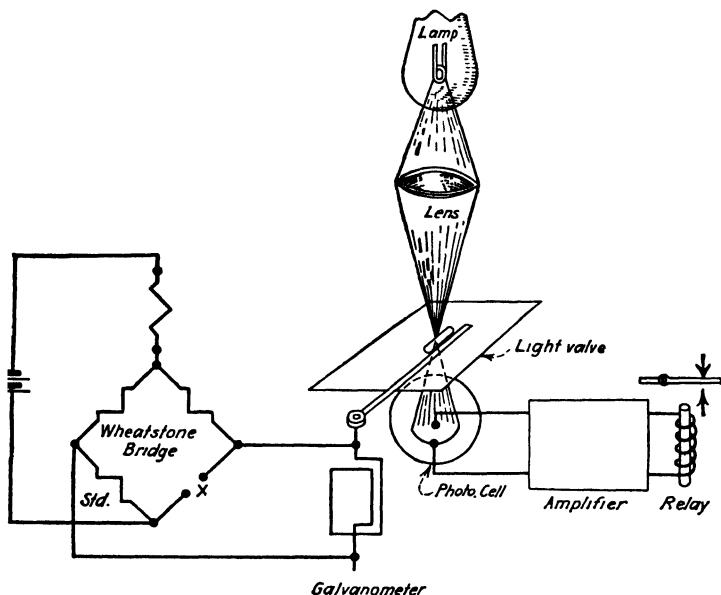
FIG. 40.—Rejection system depending upon the "hole-in-the-meter" principle.

If this deflection corresponds to the limit of variation of resistance, or is greater than this limit, the light beam will sweep across one of the photocells and operate the associated relay and ejection mechanism, and the faulty resistor is eliminated.

Automatic Precision Inspection.—One of the fields in which photocells are finding wide application is supplementing a deflection-type meter. Two examples of this are the devices used by the Western Electric Company[1] for capacitance and for insulation-resistance tests. The assembled optical system shown in Fig. 40 is used with a standard-type capacity meter to determine whether condensers satisfy the specified capacitance tolerances.

[1] TIETZ, W. J., and C. PAULSON, *Electronics*, January, 1932. The principle involved here has been employed in automatic weighing control.

The meter scale is replaced by a metal plate on which there is a slit at a position corresponding to half-scale deflection. The optical system is so arranged that, unless the slit is covered by the meter pointer, the image of a lamp filament is focused on a photocell mounted below the slit. Two of these units are used: one to check that the capacitance does not exceed the upper
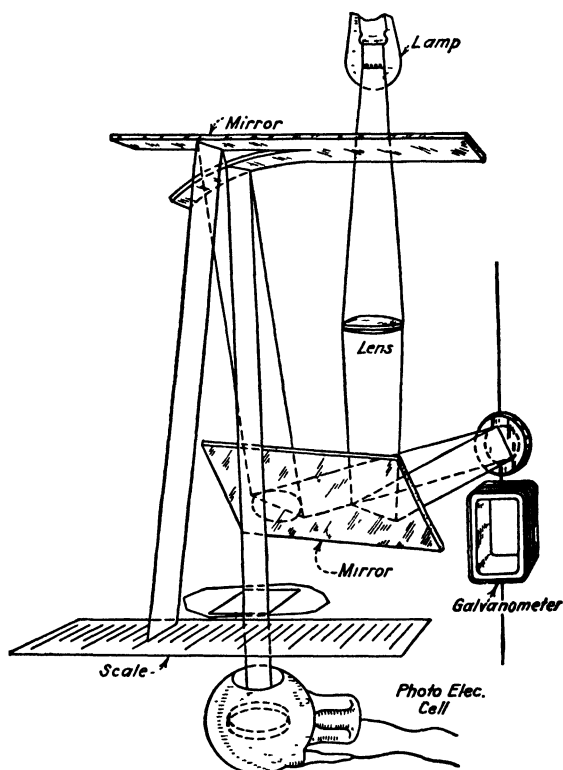
FIG. 41.—Testing of insulation resistance in the telephone plant.

limit of the tolerance, and the other to check that it is not too low. For the maximum capacitance check, the movement of the pointer is restricted to the lower half of the scale by a stop at midscale. Then with the condenser to be tested, connected to the meter by a contact making jig, the pointer will cover the slit if its capacitance is too high. The photocell will then cause a grid-glow tube to actuate an ejector mechanism which rejects the condenser. To make it unnecessary to change the device

for different values of capacitance, the meter is shunted by a calibrated variable resistance.

A similar device makes the minimum-tolerance test. The machine which incorporates both these can test condensers at the rate of 1,600 per hour.

The insulation resistance of many kinds of telephone equipment is so high that it can be measured conveniently only on a reflection-type galvanometer. Use of a photocell is about the only possible way to obtain automatic testing by this method of measurement. In the set-up shown in Fig. 41, if the resistance under test is too low, the photocell will not receive light from the curved mirror, and it will operate a suitable indicator. The straight portion of the mirror is provided for visual readings and calibration. Change in calibration for different values can be accomplished by moving the cell and slot to the right or left.

A Fluxmeter with Counter-balanced Restoring Torque.[1] A fluxmeter is essentially a galvanometer of very high critical damping resistance working out of a comparatively low-resistance external circuit. Its coil is usually suspended either on pivots or by fine fibers. In the pivot type, friction cannot be entirely eliminated, and for observing feeble currents this may introduce considerable error. In using the fine fiber suspension it is sometimes desirable to eliminate the restoring torque of the suspension, for the effect of this torque is not sufficiently suppressed by the slowing-down action of the external resistance. The device shown in the figure counter-balances the restoring torque by the following action: a long, sensitive photocell is fitted with a V-shaped slit, as shown at AB; a beam of light is reflected from the mirror of the fluxmeter and focused on the slit of the photocell, which is connected in series with a source of e.m.f. across the terminals of the fluxmeter; the e.m.f. is adjusted to such a value that, if the beam will stay at rest when at the narrow end of the slit, at any other position the current controlled by the cell develops a torque in the fluxmeter coil which just balances the restoring torque of the suspension. The slit is shaped empirically to correspond to the unequal sensitivities of the cell at different spots.

To keep the coil stationary when the beam is at the narrow end of the slit AB, a battery B_2 is connected across the potential

[1] HAWORTH, F. F., *Rev. Sci. Instruments*, February, 1931, p. 125.

divider R_2, and the potential taken off is connected in series with the 10-megohm resistor R_3 across the fluxmeter. By adjusting R_2, the potential due to stray light and thermo-electric potentials may be balanced out and the beam held stationary.
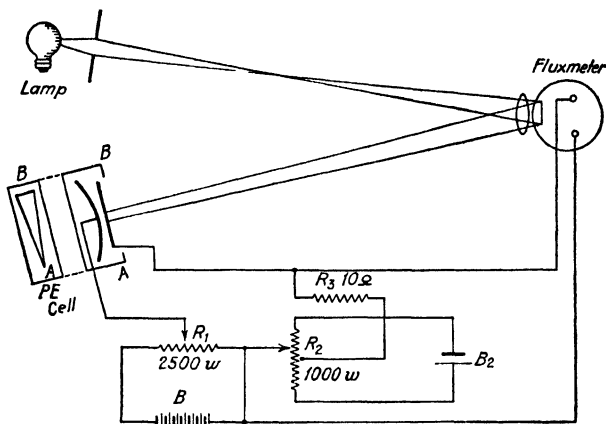
Fig. 42.—Fluxmeter using light-sensitive cell

Calibration of Watt-hour Meters.—A method of using the photocell for calibrating watt-hour meters by comparison with a known standard eliminates some of the human error involved
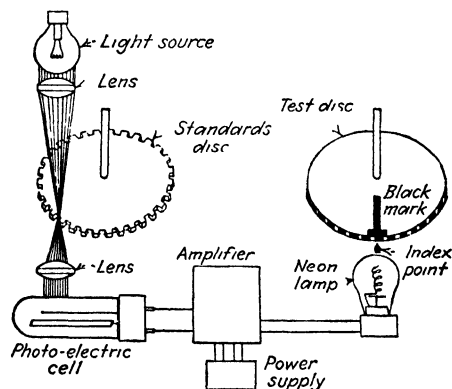
Fig. 43.—Watt-hour-meter calibrating system.

in older methods, and saves time. The method[1] is shown in Fig. 43 where the standard meter and the one to be calibrated

[1] ARONOFF, S., and D. A. YOUNG, Watt-hour Meter Testing, *Elec. J.*, June, 1929, p. 255. See U. S. Patents 1,864,627 and 1,878,658.

are measuring the same load.   The standard disk has a toothed periphery so that light can shine through the teeth onto a photo-tube.   The output of this cell is amplified and operates a neon tube. A number of notches are cut in the disk to be calibrated, the number being equal to the number of slots in the standard disk.

Thus the impulses of the light from the neon lamp will be directly proportional to the speed of the standard disk.   When the test disk seems to stand still in the light of the neon tube, the two speeds are exactly the same.

Since the two meters are of substantially the same character-istics and operate from the same source and load fluctuation, the latter will not affect the calibration.   By means of a magnifying glass the meters can be calibrated when the load is as low as 2 per cent and the number of teeth is 400.

By observing the rate at which the two disks get out of step the error of the test meter can be calculated.   In a practical case the number of slots on the standard-meter disk was 400.   There-fore, if the test disk is out of step one notch in one revolution, it is in error, fast or slow by one part in 400 or 0.25 per cent. Multiplying the number of marks out of step per revolution by this figure (0.25) will give the percentage error.

Synchronizing Conveyors.[1]—Phototubes working in combina-tion with Selsyn motors are used in a rod mill to synchronize a hook conveyor with a pin conveyor.   The pairs of pins carrying coils of rods away from the mill are spaced 10 ft. apart.   The hooks on the other conveyor are spaced the same distance apart. To successfully transfer to the hook conveyor the coils from a pair of pins, the two conveyors must run in synchronism.   It must also be possible to run the pin conveyor backward, with the hooks stopped, and on restarting, the two conveyors must synchronize automatically.

Adjustable-speed d.c. motors drive the conveyors.   To each is geared a Selsyn transmitter so that it makes one revolution while the conveyor moves 10 ft.   The stators of the two Selsyn transmitters are connected to a Selsyn differential on the shaft of which is a slotted disk.   Phototubes are mounted on one side of this disk, a source of light on the other.   So long as the two

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[1] Snyder, W. B., Synchronizing Conveyors by Selsyns and Photocells," *Elec. World,* Feb. 13, 1932.   Winne, H. A., Synchronous Ties, *Gen. Elec. Rev.,* March, 1933; also *Iron Steel Eng.,* December, 1932.

motors rotate at the same speed, the disk is stationary and no light reaches the phototube. If one motor runs too fast, light falls on the tube which through an amplifier energizes a relay which in turn sends current into an auxiliary field on the pin motor and slows it down. If it runs too slow, by another photo-tube the auxiliary field is energized in the opposite direction.

Testing Camera Shutters.[1]—The use of a phototube with an electromagnetic oscillograph has made possible a fairly simple method of testing camera shutters differing from other methods in common use. Other uses of the combination of photocell, oscillograph, and amplifier may be suggested by the application noted here.
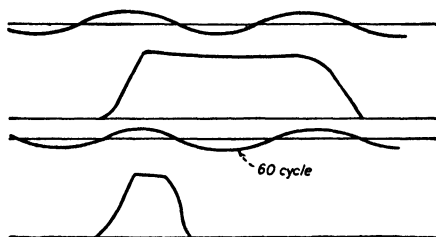
FIG. 44.—Examples of timing of shutters.

A 200-watt incandescent lamp served as the source of light and the optical system was arranged to cover the shutter with uni-form illumination. The rear camera lens converged the beam upon the cell. The shutter was released by burning out a fine wire connected to the oscillograph shutter circuit.

The output of the phototube was amplified by a direct-coupled amplifier, whose output operated the oscillograph string. A 60-mil output was sufficient for the oscillograph, a General Electric type EM.

When the photocell was dark the plate current of the first tube was high enough to overbias the 250-type output tubes and reduce the plate current to a low value. The flash of light as the shutter opened and closed produced a unidirectional pulse of current. B battery power was used. Two shutter diagrams given here show the results obtained.

Observation of Vibration in Incandescent Bodies.[2]—In many fields of research, it is desirable to obtain quantitative data on

[1] REICH, H. J., and G. S. MARVIN, *Rev. Sci. Instruments*, December, 1931.
[2] MESERVE, W. E., *Rev. Sci. Instruments*, vol. 2, No. 1, pp. 47–48, 1931.

the frequency and amplitude of mechanical vibrations in an incandescent body. For instance, the life of lamps attached to vibrating parts, such as in trains, movie projectors, etc., can be lengthened considerably by so constructing the filament that no part of it has a natural frequency of vibration equal to the frequency of the vibration to which the lamp is subjected. The data for this purpose can be obtained by passing light from the filament through an optical wedge to a photocell whose output is recorded by an oscilloscope.[1] The wedge is composed of two right prisms having the same index of refraction, one prism being of clear glass and the other of yellow glass which transmits wave lengths of 410 to 540 millimicrons. As the filament vibrates in a vertical plane, the light reaching the cell varies because it goes through varying thickness of yellow glass. The cell output is therefore a wave which, recorded on the oscilloscope, shows the frequency and amplitude of the filament vibration.

Time of Flight and Velocity Recorder.—The phototube with amplifier has been used (Aberdeen Proving Ground) to measure the time of flight and velocity of projectiles.

The amplifier in this apparatus is so arranged that it causes a spark to perforate a piece of paper which is carried on the drum of a slow-motion Aberdeen chronograph. When the gun is fired, the light from the muzzle flash causes the first spark to jump, and the burst of the projectile at a remote point of the trajectory causes the second spark. This apparatus has functioned satisfactorily for night firing, but with less certainty in the daytime, because of the great sensitivity required. When applied to the measurement of velocity of projectiles, the apparatus is so constructed that when the projectile passes overhead, a reduction in the light which impinges on the cell is recorded by means of an amplifier on an oscillograph or other instrument. This method of measuring velocities is especially suitable for the measurement of the velocity of large guns at angles of elevation too great for convenient use of the solenoid chronograph.

To obtain a record of the impact of inert bombs on the ground in connection with ballistic data and also to record the delay of bomb fuses, a very sensitive apparatus based on vacuum-tube oscillations has been made. The ground shock from the impact

[1] The Oscilloscope: "A Stabilized Cathode-ray Oscillograph with Linear Time Axis," *J. Am. Inst. Elec. Eng.*, vol. 46, p. 563, 1927.

of bombs, slight as it is, causes a change in the distance between two metal plates, whose capacity forms part of the oscillating circuit.   This apparatus has been found sensitive enough to record the impact of 17-lb. bombs on rather soft ground at a distance of 1,200 ft. from the apparatus.   The impact of heavier bombs can be recorded with certainty at a distance of a mile or more from the station.

For testing small arms a closed range for the purpose of obtaining a series of spark photographs at different points along the
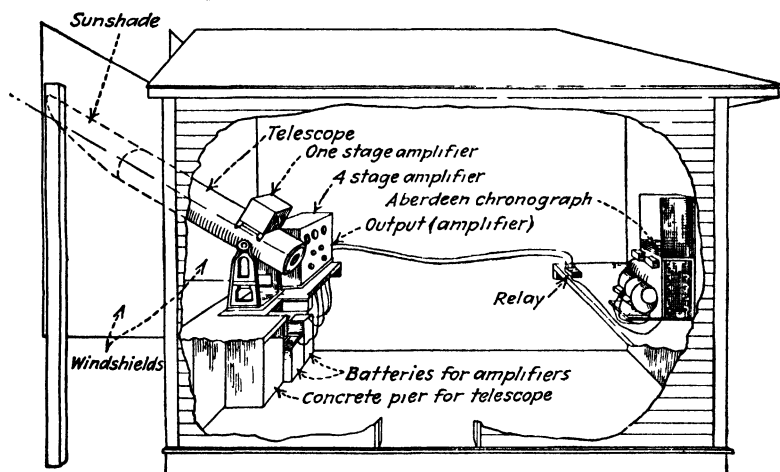
Fig. 45.—Time of flight recorder as used at Aberdeen Proving Ground.

trajectory of a given bullet and of measuring the retardation by photocells has been constructed and is now being equipped at the Aberdeen proving ground.

Phototubes Used for Catching Speeders.[1]—The policeman whose duty it is to apprehend speeding motorists has recently been given an electrical partner to aid him in his work.   A device for automatically measuring the speed of a car as it passes a given point has been developed, two photocells and a vacuum-tube relay circuit being used.   This device, designed by F. H. Shepard of RCA Radiotron Co., Inc., automatically gives warning when an automobile passes a pair of phototubes too rapidly.

As shown in the figure, initially, gas-triode A is conducting, gas-triode B is not, and relay R is open.   When the front of a

[1] *Electronics,* February, 1935.

car interrupts light to the first photocell, the cell current decreases sharply, and the grid of tube B is charged positive. This starts tube B conducting. The cathode of tube B was initially at ground potential but is now positive; so C_1 applies a positive potential to the cathode of tube A and stops conduction in tube A. When light on the second cell is intercepted, current through the second cell decreases sharply, and a reverse procedure takes place: the grid of tube A is charged positive, tube A starts conducting, the cathode of tube B is pulled positive, and tube B
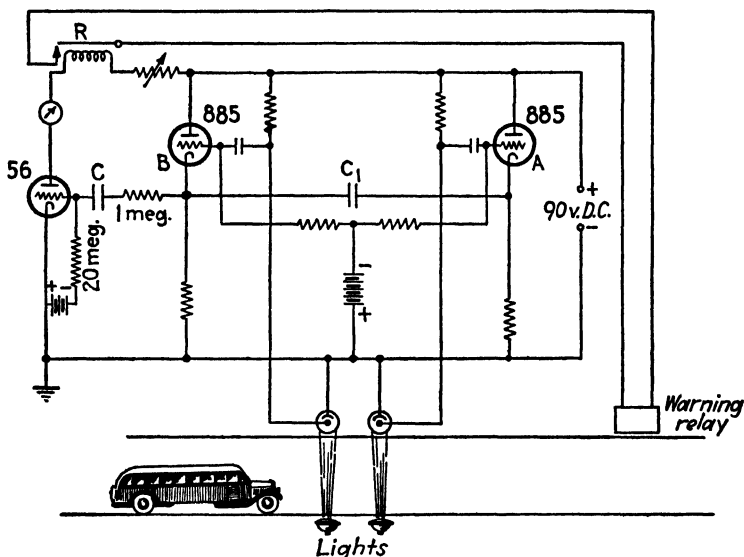
FIG. 46.—Photo-electric automobile speed trap.

stops. It will be seen that tube B conducts only during the time that it takes the car to go the distance between the two phototubes.

When tube B starts conducting and its cathode jumps to a positive potential, C pulls the grid of the 56 as far positive as electron current from the filament will permit—to about zero potential. This increases the 56 plate current to close relay R. While tube B continues to conduct, condenser C charges up through the 1-megohm resistor because there is a potential difference between the positive cathode of tube B and the zero-potential grid of the 56. When tube B stops conducting and

its cathode returns to ground potential, condenser C applies a negative voltage due to this accumulated charge to the grid of the 56. The magnitude of this voltage depends on how long tube B was conducting which in turn depends on how slowly the car passed the phototubes. If a large enough negative voltage is placed on the grid by the condenser, plate current through the 56 will be decreased below the release value of relay R. Therefore, when a slow car reaches the first phototube, it will close relay R; when it reaches the second phototube, it will open relay R before the warning relay, which is relatively slow acting, can close. A fast car, however, will actuate the warning relay because relay R will close and stay closed.

By the time the car has passed both phototubes and light is shining on them again, the charge on C has leaked off, plate current of the 56 has returned to normal, and everything is set for the next car. The circuit is so adjusted that normal plate current through the 56 is less than the pull-over value of the relay R but greater than the release value; so when a fast car fails to open relay R after closing it, the relay will remain closed even after the current through it returns to normal. Therefore, once the warning signal is turned on by a fast car it will stay on for any number of fast cars following and will be turned off only by a slow car. After that, it will stay off for any number of slow cars and will be turned on again by a speeder.

By changing the details of installation, this circuit can be used in many different applications. The installation diagrammed is for a single line of traffic. For two lines of traffic going in the same direction, such as is found on four-lane highways, bridges, and vehicular tunnels, a vertical beam of light can be used for each lane. By mounting the light source and phototube in a hood overhead, in conjunction with a mirror buried at the lower end of a vertical pipe sunk in the road, trouble due to sunlight and other stray light is avoided. By placing the warning signal in a prominent position along the road, the speeder can be cautioned; by placing it in a police booth, he can be caught. By adding a recording mechanism to the circuit, 24-hr. surveys can be made automatically for insurance companies or traffic engineers of speeding conditions at such points as the entrance to a small town on an express highway or the approach to a railroad crossing. By replacing

the relays with a d.c. milliammeter calibrated in miles per hour, an accurate measurement can be made of the instantaneous speed of racing vehicles.

Tension Regulator.—A novel means of maintaining constant tension when separating impregnated tire cord from the canvas liner before the former goes to the tire builder has been installed by a large tire manufacturer. The impregnated cord hangs in a loop, the bottom of which hangs part way between a light source and a photronic cell. If the loop becomes too long, the
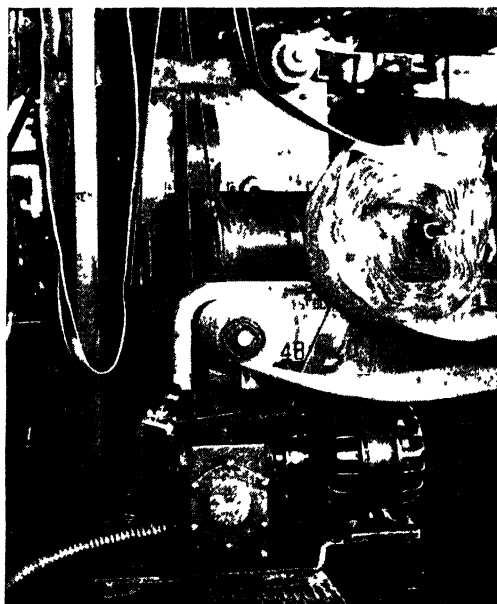
Fig. 47.—Tension regulator using dry-disc type of light-sensitive cell.

light beam is interrupted, and the speed of the winding drum is automatically adjusted to take up the slack. If the loop becomes too short, so that there is a direct pull on the canvas liner, the "electric eye" makes a similar automatic adjustment of the speed at which the tire cord is drawn off.

Water-level Indicator.[1]—A simple and reliable water-level indicator may be constructed as shown in Fig. 48. The light beams are aimed so that they strike the gauge glass at an angle. When there is no water in the glass, the beam of light strikes

[1] LAMB, A. H., *Power Plant Eng.*, July, 1933.

straight through and passes by the cell; however, when water
is present, the beam is refracted and falls directly on the cell,
causing the meter to indicate. There may be any number of
cells, and the meter will read in direct proportion to the number
of cells illuminated, thus indicating the height of water in the
glass.

If a simple alarm is desired, it is required only to use one light
beam as explained above, or a float may be used. When the
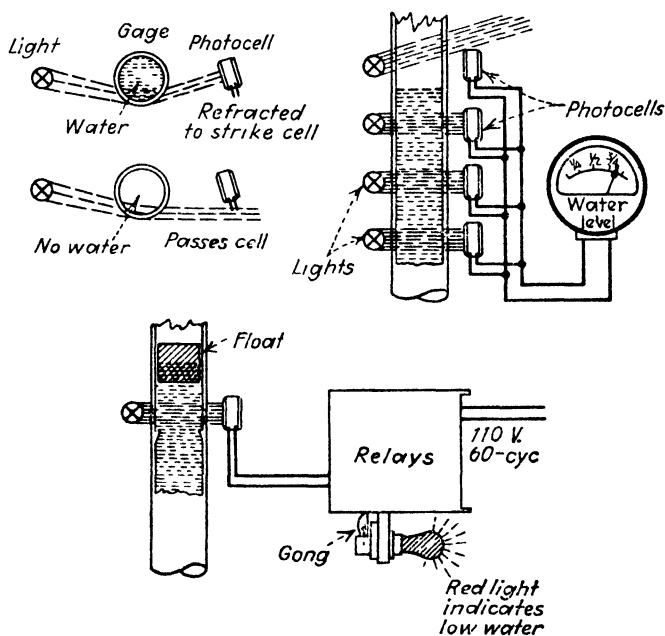
Fig. 48.   Water-level indication.

predetermined low level is reached, the float intercepts the light
beam and causes the relay to ring a gong and turn on the red
light.

Piston-pin Inspection. - A good example of recent application
of phototubes to heavy industrial operations may be found
in the wrist, or piston-pin, inspector developed by R. E. Powers.[1]

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[1] *Electronics*, September, 1935.   Other devices developed by Powers and
applied to automobile manufacture will be found in this reference and also in
Electronics, June, 1936.

In this device one-tenth of a thousandth of an inch change in diameter causes a shadow movement of about ¾ in. Roughly speaking, the optical magnification is of the order of 7,500 to 1; and because the intensity of the light falls off by the square of the magnification, a fairly sensitive light relay is required. When measuring to one-tenth of a thousandth of an inch, a small amount of light must be used as the original source, because any excessive heat generated by this source would cause expansion of the article, and all accuracy would be lost. (An ordinary piston pin, at 68°F., held in the hand for about 25 sec. will expand over one-tenth of a thousandth of an inch.)
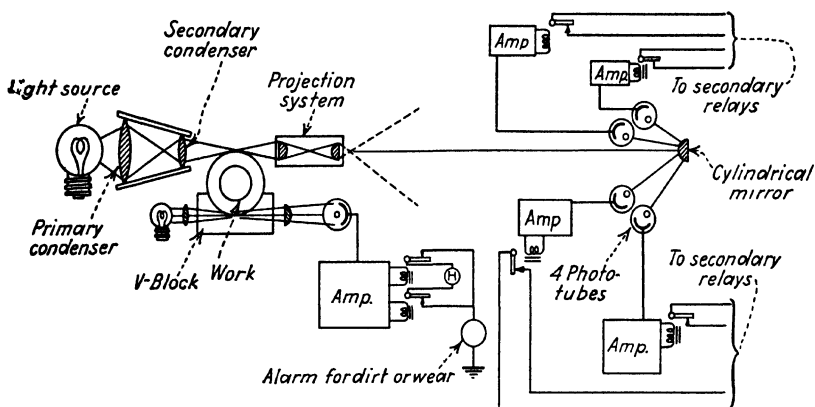
Fig. 49.—Optical system for piston-ring sorting machine.

In operation the piston pin, or other work, comes to rest on a V block, the contact surfaces of which are fitted with tungsten carbide inserts to reduce wear to minimum. An image of the lamp filament is focused on the center line, or diameter, of the piston pin. The projection system is then brought in focus with the diameter, which is brightly illuminated by the filament image, and a shadow of the piston pin is projected to the lower part of the machine, where it is picked up by the cylindrical mirror. The cyclindrical mirror projects the light back to the phototubes, and as the piston pin increases or decreases the shadow moves to eclipse the various cells.

A secondary relay circuit sorts and grades according to piston-pin diameters as follows:

Diameter 0.85909 in. or smaller is undersized and scrapped.
Diameter 0.8591 to 0.85919 is the small pin and is so graded.
Diameter 0.8592 to 0.85929 is the standard pin and is so graded.
Diameter 0.8593 to 0.85939 is the large pin and is so graded.
Diameter 0.8594 or larger is oversized and is returned to be relapped.

It will be noticed from the foregoing dimensions that a very critical change-over point from one size to the next is necessary. This change-over occurs on less than one-tenth of a tenth of a thousandth of an inch. The machine described sorts the *small* pins into one container, the *standard* into another, and the large into still another. The oversized pins are refinished and remeasured. The undersized pins are scrapped.

If the piston pin being measured is undersized, all four cells are illuminated, and four secondary relays are all energized; if the pin is small, one cell is shadowed, three illuminated; if the pin is standard, two cells are shadowed, and one illuminated; and if the piston pin is oversized, all the cells are shadowed.

The use of four phototubes and four amplifiers with four primary or sensitive relays allows immediate replacements of a complete amplifier chassis at time of a tube failure; adjustments are not critical, and operation is foolproof. The same general outlay as used in this machine may be used for any number of measuring and grading operations where speed and accuracy are necessary.

Photoelectric Control for Time Record.[1]—A PJ 23, operating into a 885 (a.c. operated), is used to provide a time record on the seismograph in the Department of Geology at Cornell University. A vane of black paper on the end of the second hand of a clock interrupts the beam once each minute. A small electromagnet in the plate circuit of the 885 causes a hammer to strike the recording needle support, working the smoking-drum record. Since it is very important that the record be continuous, the possibility of a filament burn-out in the light source was provided for by lighting the two filaments of a headlight bulb in parallel from a 6-volt coil of the transformer through a resistance of approximately 0.5 ohm. Since each filament draws 2 amp., the voltage across the lamp is only 4 volts; but if one filament burns out, the voltage across the lamp increases to 5 volts, the regulation of the transformer and the increased resistance of the remaining filament both tending further to increase the voltage

[1] BENNETT, JOHN A., *Rev. Sci. Instruments*, July, 1935, p. 204.

across the lamp.   Thus it was found that with this arrangement one filament would give as much light as two.

Temperature Control.—Numerous applications of electron tubes, especially phototubes, have been made to temperature measurement and control. One of the simplest is shown in Fig. 50, where the mercury in a thermometer rising as a result of heat applied to a furnace, for example, shuts off the light from the phototube and cuts off the heating current. The mercury will then fall and permit light to fall on the sensitive surface
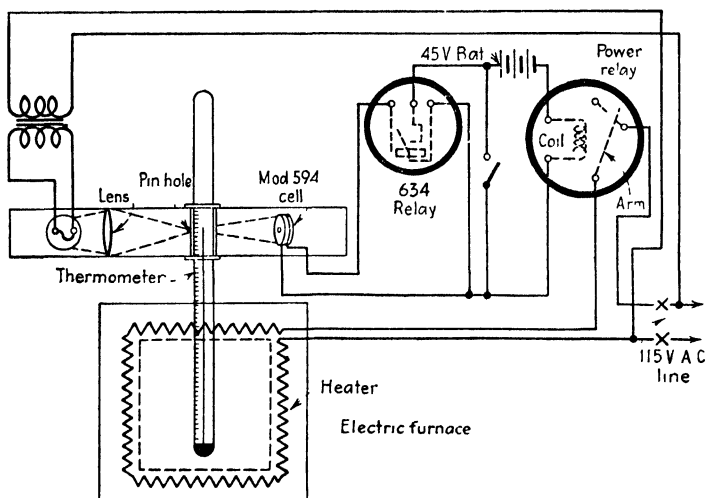
Fig. 50.—Simple and effective use of dry-disk phototube-temperature control.

which will close the power relay and turn current into the heater.

Automatic Temperature Control. – An interesting method of controlling the temperature of filament coating ovens is described by W. P. Koechel.[1]

In this particular case it was desired to set the temperature of the oven, and leave it to the efficacy of the system to be described to maintain that temperature within very close limits. The method employed is applicable to many other uses.

In the oven was installed a thermocouple junction connected to a millivoltmeter. This meter is mounted with a suitable light source focused on the midportion of the scale. In a light-

[1] KOECHEL, W. P., *Electronics*, May, 1932, p. 170.

proof compartment behind the meter was a photocell. In the center of the meter scale were a round aperture and a corresponding hole in the bakelite case so lined up that the rays of light travel through the aperture and fall upon the phototube.

The hole in the indicator was in such a position that when the needle read in the exact center of the scale the aperture was closed and no light could get through to the phototube. The photocell was connected to a grid-controlled rectifier and asso-
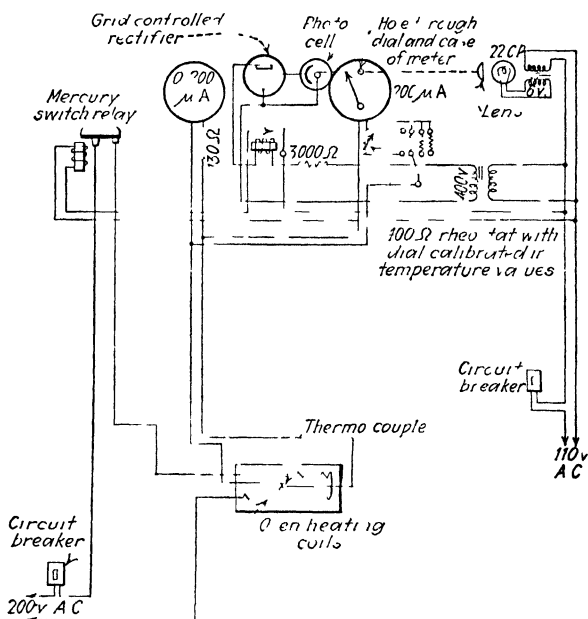
Fig. 51 —Automatic temperature control on filament coating oven

ciated relay system so arranged that it would connect and disconnect the line voltage to the oven under control

The sequence of operation is such that, when the temperature of the oven is below any selected standard value, the meter indicator is on the lower half of the scale. Under these conditions, the rays of the light source reach the photocell and so operate the relays and connect the power line to the oven. This condition exists until such a time as the temperature of the oven rises to the point equivalent to that required to give a meter indication in the center of the scale. Under such condition, the aperture of the meter is covered by the indicator. This cuts off

the light from the photocell, and actuates the relay system cutting off the power supply from the oven.   With the power off from the oven, the temperature decreases until the indicator of the temperature meter uncovers the hole in the center of the scale.   This again permits light to reach the photocell and the above cycle is repeated continuously.

A calibrated variable resistor, in series with the temperature meter, permits setting this meter so that it will read at the exact center of the scale for any required temperature setting.   The dial controlling this variable resistor can, therefore, be calibrated directly in temperature values.   When the dial of the variable resistor is set for any given temperature setting, it means that the temperature meter (millivoltmeter) will indicate at the exact center of the scale when the oven reaches that temperature and, therefore, covers the aperture.

The mechanical construction of the Weston Model 301 meter makes it simpler to drill the hole through the center of the case and scale than at any other point.   A stop is necessary to prevent the needle from overshooting and by uncovering the aperture turn even more heat into the oven.   The sensitivity of this system is a function of the strength of the light source, sensitivity of the photocell and of the ratio of the scale aperture to the width of the pointer which covers it.   With a focused light source of 21 cp. and a photocell with sensitivity of $30\mu a$. per lumen, and a $\frac{1}{16}$-in. aperture in a Model 301 meter, it is possible to maintain temperature values in the oven of within 0.5 per cent of the range being used.

Photocell Controlled-rectifier Temperature Control.—Another use of the photocell method of controlling temperature has been made by Anderson[1] in the preparation of single metal crystals in which it was necessary to hold a quantity of zinc at its melting point for periods of from 12 to 48 hours by surrounding it with a bath of zinc automatically maintained in two-phase equilibrium through the abrupt change in resistance attending isothermal fusion.   Use is made of the fact that at the melting point the specific resistance of molten pure metal is about twice that of the solid metal at the same temperature.   Thus, if contacts are immersed in the metal and a constant direct current is passed through it, the voltage drop across these potential contacts will

[1] ANDERSON, P. A., *Rev. Sci. Instruments*, December, 1930.

be a function of the quantity of metal that has melted.   This variation in potential may be used, for example, to control the heating current in a furnace.

In the diagram, F is the furnace thermostat, M the zinc bath. Tungsten potential contacts connected to a galvanometer (a Moll instrument with negligible zero shift and a voltage sensitivity of 5×10^{-6}) and tungsten current contacts leading to a 2-volt storage battery are immersed in the bath.   Light from the
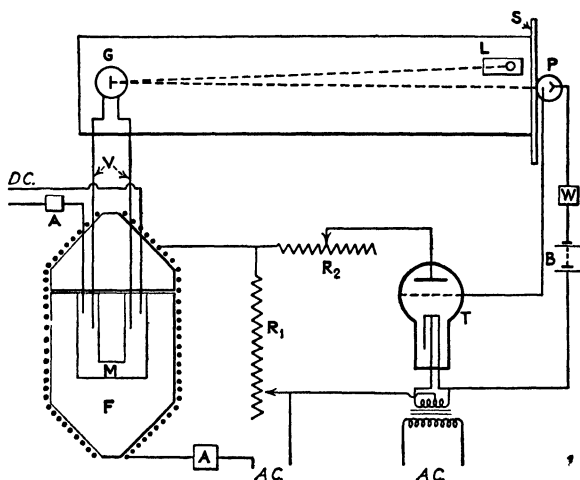
Fig. 52.—Photocell controlled-rectifier method of maintaining constant temperature of a bath.

lamp L is reflected from the mirror of the galvanometer to a photocell which controls the grid-controlled rectifier.

Heating current enters the furnace through a parallel circuit composed of R_1 and the plate circuit of the tube.   In operation full current goes into the furnace until the resistance of the bath falls when the light spot shifts away from the photocell and the tube bias is increased to the point where the discharge is extinguished.

Anderson reports that the resistance of the zinc bath was of the order of 1×10^{-5} ohm in the solid state and twice this in the liquid state.   With a control current of 20 amp. the potential drop during fusion was about 2×10^{-4} volt and the galvanometer deflection was 40 mm.   A change of 2 mm. was sufficient to operate the photocell.

Another method (by J. V. Kovalsky) of controlling temperatures by a photocell is shown in Fig. 53. Here light is focused upon the phototube when the temperature is low. The amplifier is so arranged that when light is on the phototube, the heater contacts are closed. Thus when the lamp, or the phototube, or control voltage fails, the power is disconnected.

When the temperature is low, the beam of light is focused upon the stationary mirror and thence to the phototube. Power is
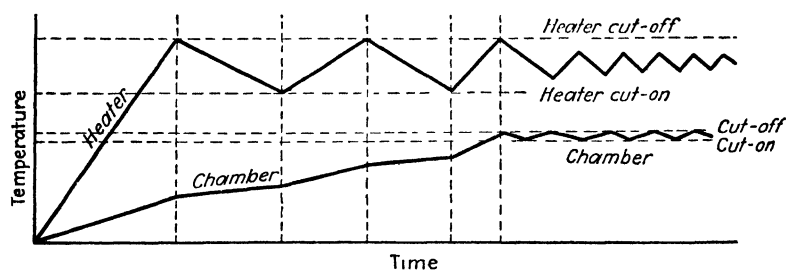
Fɪɢ. 53a —Response characteristic of circuit of Fig. 53b.
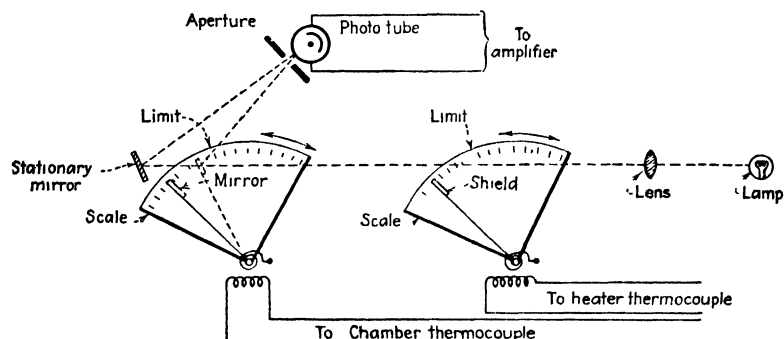
Fɪɢ. 53b.—Temperature control that will maintain oven to within $\frac{1}{2}$° in 1500°F

applied to the heater in the furnace. As the temperature of the furnace chamber rises, the heater temperature reaches a maximum and may burn out if left on for appreciable time. Therefore the circuit is so arranged that the shield on the pointer of the heater thermocouple meter intercepts the light and opens the power contacts. The chamber continues to heat, however, due to the stored heat in the walls and the heater.

The heater temperature falls and the shield is removed from the path of the beam permitting the light to fall on the mirror again. As the chamber temperature rises and the thermocouple

meter measuring the chamber temperature indicates this increase, a mirror on the indicating device picks up the light and continues to reflect it into the phototube until the temperature reaches some upper limit desired when the light beam is reflected at such an angle that it no longer falls upon the phototube. Then the amplifier opens the power contacts and the temperature begins to fall. Soon, however, the light is again reflected into the phototube and the cycle continues.

The limits of temperatures on both the furnace chamber and the heater can be changed by turning the meter unit on the
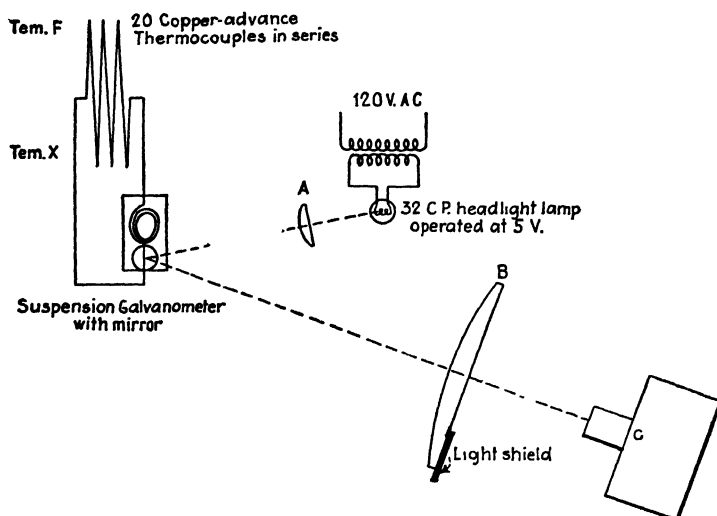
Fig. 54.—Temperature control used at Electrical Testing Laboratories.

axis of the pointer. Tests show that the temperature at constant load in furnaces is kept so close to the limit that with the present-day recording instruments it is impossible to see any variations. The variation was estimated to be approximately $\frac{1}{2}°$ in 1500°F., as compared with 10° on standard instruments.

Still another temperature-control circuit[1] using a light-sensitive relay has been used at Electrical Testing Laboratories, Inc., to prevent heat drain along connecting leads used in thermal measurements on electrical apparatus. A group of 20 copper-advance thermocouples connected in series have their opposing junctions at the two points to be maintained at the same tempera-

[1] SHARP, C. H., *Electronics*, September, 1932, p. 284.

ture, F and X. The circuit is closed through a reflecting galvanometer. If the two points are at the same temperature, the beam of light reflected from the galvanometer mirror falls on the photocell. The point X tends to be cooler than the point F, and when this difference in temperature exceeds a certain amount, the light beam leaves the photocell which causes a relay in the amplifier-tube circuit to throw into the circuit a heating element.

A precision method[1] of maintaining temperature of an oil bath is shown in Fig. 55. A galvanometer is used whose deflec-
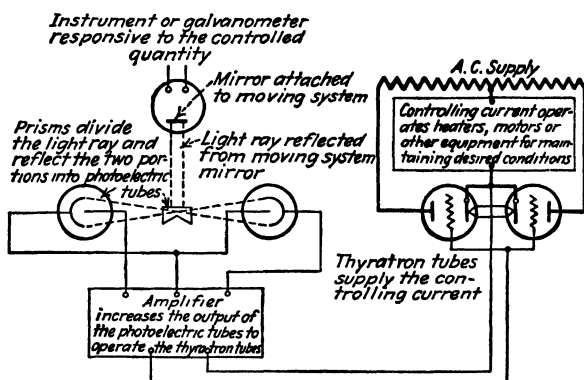
FIG. 55.—Temperature control of high sensitivity.

tions are caused by variations in the voltage generated in a copper-manganin thermojunction immersed in the oil. A beam of light reflected from the mirror of the galvanometer into one of two photocells increases or decreases the temperature accordingly, through an amplifier and grid-controlled rectifiers, by changing the heat-coil current.

In a three-weeks test the temperature was kept constant at all times within 0.003 to 0.005°C.

Inexpensive Temperature Control.[2]—The novelty in the circuit of Fig. 56 lies in the logical combination of inexpensive items of standard equipment into a controller which will give results that compare very favorably with the work of expensive commercial instruments.

[1] LaPierre, C. W., *Gen. Elec. Rev.*, July, 1932.
[2] Weinland, C. E., *Electronics*, July, 1935.

The temperature of the furnace A is to be controlled in accordance with the e.m.f. indication of the thermocouple B. The contact on the slide wire C is first set to the potential that the thermocouple will develop when the furnace is at the desired temperature, by throwing the switch to position D, when the potential can be read on the potentiometer F. By throwing the switch to the operating position E, the thermocouple is
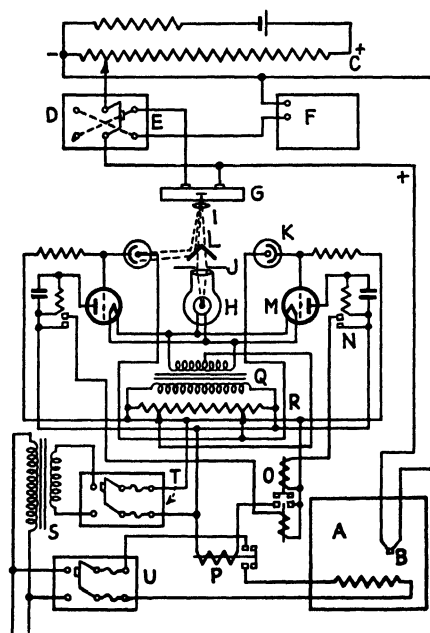
Fig. 56.—Temperature-control circuit using inexpensive components.

connected through the L & N type-P No. 2239-C wall-type galvanometer G, in opposition to the slide-wire potential, so that when the two potentials are equal, no current will flow through the galvanometer, and it will not deflect. Then any change in thermocouple potential will result in a galvanometer swing one way or the other.

The filament of a 6-volt, 21 cp. automobile lamp H is imaged by a lens upon the mirror of the galvanometer, where another lens I images the slit J upon either of the photocells K (type 868) by reflection in one of the two mirrors L. The photocell current

is amplified by the corresponding 71 tube *M* and operates the sensitive Struthers Dunn CSB-51 relay *N*, which in turn operates the corresponding coil of the mechanical-latch electrical-reset relay *A* (Struthers Dunn CS600C), which controls the power relay *P*. Current for the 5-volt tube filaments and the lamp is supplied by the low-voltage transformer *Q*, while grid and photo-cell anode potentials are secured from the variable 5,000-ohm voltage divider *R*. All power to operate the regulator circuit is supplied by the transformer *S*, through the switch *T*, while furnace-heating power may be shut off by opening the line switch *U*.

In putting the controller into operation, the thermocouple circuit switch is first thrown to position *D*, when the galvanometer is short-circuited through this switch and may be adjusted for zero so that the reflected light beam falls on the apex of the mirror angle, while at the same time the potentiometer *F* will be connected to read the potential setting on the slide wire *C*, which should be adjusted to the value corresponding to the desired furnace temperature. When the switch is then thrown to position *E*, the galvanometer will deflect and through the actuated photocell and relays turn on the furnace power, which will then remain on even though the galvanometer beam swings on past the photocell and, in fact, until the beam has returned past center and has actuated the photocell on the other side, causing it to trip the mechanical-latch relay and break the power circuit.

If a low-resistance slide wire *C* is used, a protective resistance may be required in series with the galvanometer. On the other hand, with a high-resistance slide wire the protective resistance may be omitted, with a resulting gain in sensitivity. Ill effects from overdamping the galvanometer need not generally be feared.

In an on-off control circuit of this type, one must usually choose between a thermocouple location close to the furnace charge or one close to the heating element. The former will result in close control of average temperatures but with wide swings between maximum and minimum due to the temperature-time lag between heating elements and thermocouple, while in the latter case a thermocouple location in intimate contact with the heating element itself will greatly reduce temperature

oscillations but at the same time will introduce variations in mean temperature of the charge which may or may not be systematic. In cases where a large proportion of the required power can be supplied continuously to the furnace, with the controller handling only a small variable portion, much better temperature control can be obtained. In many cases, and the higher the furnace temperature the most likely the case, care must be exercised to ground the thermocouple or to shield it electrically from the heating element, or erratic operation may result.

A controller utilizing this circuit operates a 440-volt, 18-kw. Globar furnace at various temperatures up to 2500°F. Considering the controller alone, the thermocouple potentials corresponding to the "on" and "off" operating points may easily be made less than 0.1 voltmeter.

Hole-in Meter Use.—The simple expedient of boring a hole in a volt- (or other) meter at the point in the scale at which some control function is to come into play, and then shining a beam of light on the meter with a phototube behind it to intercept the beam when the meter needle moves from the proper position, is used often. For example, Fig. 51 shows a good usage. Another is shown below.

Voltage Supervisor.—In a tube-manufacturing plant where vacuum tubes are tested before shipment, the voltages used for test must be carefully maintained at the desired values.

This phototube is connected to the input of the amplifier so that light on the cell increases the negative bias on the amplifier tube and reduces the plate current to a negligible value. The amplifier tube relay is continuously energized as long as the phototube is in a "dark" condition. The operation of the photocell causes this relay to drop to the nonoperative condition, energizing a second relay which in turn operates a pilot light and gong. This second relay also acts to disconnect the motor driving a commutating device. In addition, there are a number of small pilot lights, one for each voltage circuit being supervised. These small pilot lights indicate which particular circuit is indicating an abnormal voltage.

The monitoring meter is connected in proper sequence to each of several circuits for about 3 sec. in every 80 sec. The commutating device consists of three sections of 20 contacts each, together with three rotating arms and brushes. Two of these

commutators make the connections to the monitoring meters, while the third operates the alarm signals.

When the alarm functions, the motor stops and causes the pilot light corresponding to the circuit in trouble to stay lit until the trouble is corrected. To prevent the motor from coasting beyond the proper commutator point after the current is cut off, an electric braking scheme is utilized, in which 6 volts

Fig. 57.—Supervisor making certain that voltages are correct in tube testing.

direct current is applied to the motor at the instant that the 110 volts alternating current is removed. This acts as a very effective and silent brake, and the speed at which the motor decelerates can readily be controlled by varying the applied d.c. voltage.

In using this master control system, the voltage values are first adjusted manually at the control panel. As each voltage circuit is supervised once every 80 sec., it is almost impossible for an abnormal voltage condition to persist. When the alarm is sounded, the faulty voltage is manually reset to its proper value.

Photocell Voltage Regulation.[1]—The hole-in-meter trick has been applied to generator-output control. The generator in this particular case was a 250-volt d.c. unit. The tube plate current must be capable of handling the entire field current or several tubes may be placed in parallel.

The plate impedance of the tube, or tubes, is substituted for the usual field rheostat. This resistance is varied by the grid bias of the tube, and as a phototube has control over the grid bias, the phototube becomes the controlling unit in the system. This cell is mounted behind the indicating meter, and a hole is bored through the dial at the point which indicates the proper field voltage. A source of light and a spherical mirror are placed in front of the meter.

When the aperture is uncovered by the meter indicator, the full illumination falls on the photocell. This will cause the maximum bias to be applied to the tube and thus the highest plate resistance will be in the generator field, reducing the voltage to its lowest value. When the aperture is covered, the minimum bias is placed on the tube, and the highest generator output will be secured. The change in voltage permitted will vary between the values represented by the width of the slit in the meter dial. If the width of the slit represents the distance the indicator moves for a change of 1 volt, the output of the generator will vary between plus or minus 0.5 volt of the specified value.

Photo-electric Frequency Regulator (Westinghouse).—This device is designed to hold constant the speed of a generator by applying corrective action to the prime mover which drives the generator. But it can also regulate any other machine, a steam turbine, for example, where the corrective action would be applied to the governor setting. Furthermore, it can be used on any size machine from the largest turbine to a small pilot generator which monitors the speed of a motor.

The device is very simple. A mirror is mounted on the pointer of a frequency meter connected to the machine being regulated. When the frequency is too low, this mirror turns and reflects a beam of light to one photocell; if too high, the mirror turns in the opposite direction and sends light to the other cell. Light on

[1] KOECHEL, W. P., *Electronics*, March, 1934. See also KERSTEN, H., An Automatic Current Regulator for Gas X-ray Tubes (Uses Weston Photronic Cells), *Rev. Sci. Instruments*, January, 1934.

either cell will cause a relay to close, and the proper corrective action will be applied to the field rheostat, governor, etc., as the case may be.

Antihunting is achieved by a rotating disk which interrupts the light from the mirror. A slot is cut in the disk and the disk
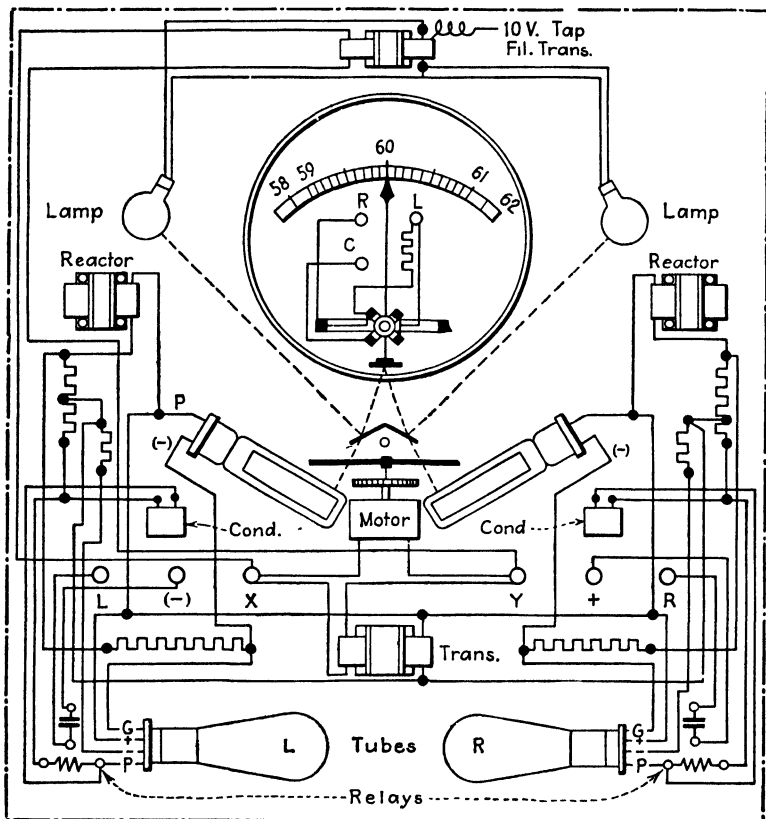
FIG. 58.—Frequency regulator employing two photocells.

speed is such that the slot lets light through once every 2 sec. Therefore the cells are permitted to impose the corrective action for a limited period of time only. But the shape of the slot is such that the greater the deflection of the mirror, the longer will be the duration of the corrective action. So the device brings the frequency back to normal at a rate which is roughly proportional to departure from normal and does not overshoot.

Phase Control of Grid-controlled Rectifier by a Phototube.—
A diagram of Cutler-Hammer equipment for controlling flow of
power by a phototube is shown in Fig. 59.

The FG-65 grid-controlled mercury-vapor tube amplifies the
current from the photocell and so, too, controls the relay.

The combination of the midtap transformer winding S and
R and C form a phase-shifting bridge making a voltage E_1
adjustable with reference to E_a (voltage across the plate-filament
circuit of the FG-65 tube). During the negative half cycle of E_a
a charge is drawn to the grid side of C_g through the cathode-grid
circuit due to the rectifying action of the tube. E_c is the con-
denser voltage and is opposite to and approximately equal to E_1.
In the negative half cycle, E_c will fall off until a point is reached
where E_c cannot reduce as rapidly as E_1 (call this point P).
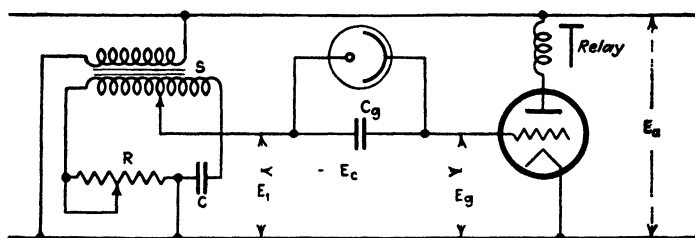
Fig 59 —Control of gas triode by phototube.

E_c will discharge through the photocell, as C_g cannot discharge
back through the cathode-grid circuit in the way it was charged
due to the rectifying action of the tube. Up to this point the grid
is at approximately cathode potential (slightly higher during the
process of charging C_g). The net grid voltage is composed of
the sum of the voltages E_1 and E_g. However, beyond point P
the summation of E_1 and E_c will result in a net negative potential
on the grid. This potential will react upon the tube and cause the
FG-65 to be nonconductive at the next positive half cycle.

The discharge from point P onward is representative of the
condition when very little light is falling upon the cell. The
discharge will then take a long time and the FG-65 tube will not
conduct until the illumination on the cell returns to normal.
When the illumination has been restored, the discharge will
take place. The net negative potential on the grid E_g will not
be sufficient to stop the tube at the beginning of the positive half

cycle, and conduction in the tube will start.   This will bring in the relay and the circuit will again be established.

The rheostat R is adjusted to correct for variation in phototube resistance which in turn is dependent upon light intensity and construction.   Thus, adjustments may be made when a new tube is placed in a relay panel or when the operating conditions change.   The adjustment shifts the voltage E_1 with respect to E_a and gives a point of sharper cut-off.

Power-plant Control.—A method[1] has been perfected by which schedules of operation can be predetermined for small hydro-plants and drawn in the form of a graphic chart which a photo-electric control mechanism will follow, actuating the devices which manipulate the gates to obtain the desired output.   Such a device has been controlling the periods of operation and the output of the unattended Llano River station of the Texas Power & Light Company.

The device consists fundamentally of a source of light, a paper chart, a drive for the paper chart, a phototube, an amplifier, a means of biasing the amplifier-grid potential, two sensitive relays in series, a tube voltage regulator, two auxiliary relays, carriages for supporting the photocell and light source, a motor for driving these carriages in such a manner that the center lines of the light source and photocell are common and in moving trace a line which is at right angles with the motion of the paper chart and a precision potentiometer geared to the carriages.   Thus a plant, or process, can be controlled automatically to carry out a complete routine.

The operation in general is as follows (refer to schematic wiring diagram, Fig. 60): A high-intensity lamp projects a beam of light through a $\frac{1}{16}$-in. diameter quartz rod, through the paper chart into the photocell.   The paper chart is a strip chart similar to those used in graphic wattmeters.   It is of standard width and a week long, assuming a longitudinal progression speed of 2 in. per hour.   It has a line of opaque black ink drawn on it tracing out the desired variations in generator load.   The chart, theoretically, should be opaqued between the traced line and the bottom or zero-load reference point, making the lower portion of the chart opaque, while the portion above the traced line is

[1] FIES, JOHN, Photocell Control Executes Predetermined Hydro Operation, *Elec. World*, Sept. 23, 1933.

left translucent. Actually it is necessary only to add enough opaque ink below the traced line to make the opaqued portions at all places of greater width than the diameter of the quartz rod.

The plate current of the amplifier tube varies with the intensity of light on the photocell. With maximum light passing through the paper chart into the photocell, there is a plate current of approximately 9 ma.; with no light on the photocell there is a plate current of approximately ½ ma. Therefore, when the
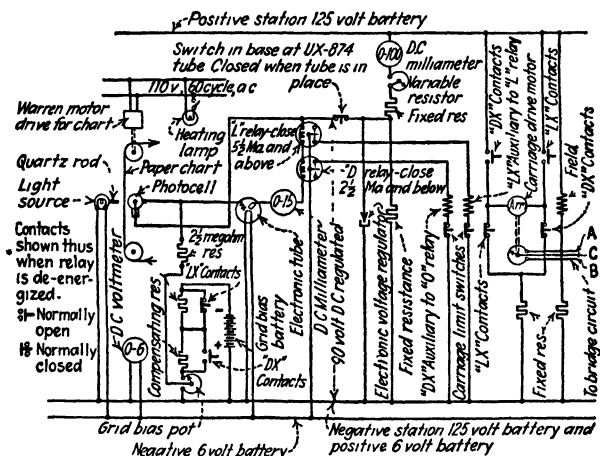
Fig. 60.—Ingenious system of making a power plant follow a predetermined performance chart

light source and photocell traverse the chart, there is a plate current of 9 ma. on the translucent side of the traced line and ½ ma. on the opaqued side; also, there is a position over the line tracing between the opaque and translucent sides where the current is approximately 4 ma. The plate current passes through two sensitive relays in series. One of the relays is calibrated to close at and above 5½ ma. The other relay is calibrated to close at and below 2½ ma. Thus, it is evident that when the light is on the translucent portion of the chart the 5½-ma. relay is closed, that when the light is on the opaque portion the 2½-ma. relay is closed and that there is a position half way between the translucent and opaque positions where both relays are open.

Auxiliary relays are used in the device because the sensitive relays have very little contact capacity. The auxiliary relays

operate to energize the carriage drive motor, which is reversible, to drive the carriage toward the translucent or opaque sides of the tracing, as prearranged, to always bring the center of the projected light toward the intersection of the two portions; that is, over the traced line when both sensitive relays are open. Thus the light beam follows the edge of the curve as the chart passes under it. The line may be smooth or irregular, but the light source will always maintain a position centered on the edge of the tracing. If for any reason the light should cross the opaque line, it will travel to the zero limit and will no longer be controlled by the curve until picked up again at some zero point
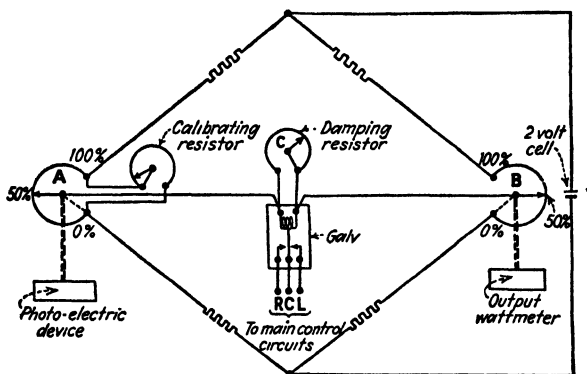
FIG. 61.—Control bridge utilizing two potentiometers.

of the curve. The zero and maximum points are established by limit switches attached to the carriages.

The varying density of the paper chart, the light blue coordinate lines and the minute irregularities of the edge of the opaque curve cause the sensitive relays to be "nervous" when the paper chart is moving, due to the extreme sensitivity of the photocell. When a relay is nearly closed, its contacts would chatter without some form of compensation. Compensation is accomplished by placing resistors in series with the grid-biasing potentiometer (Fig. 60) and cutting in and out these resistors by means of extra contacts on the auxiliary relays to raise or lower the grid-bias potential and cause the plate current to increase or decrease a slight amount and thus require a greater variation of light on the photocell to open than is required to close the contacts of the sensitive relays.

The photocell anode and the amplifier plate circuits are maintained at a positive 90-volt d.c. potential obtained from the station battery and regulated by a standard type of electronic-tube voltage regulator.   The carriage drive motor is arranged for quick reversing and dynamic braking.

A bridge circuit (Fig. 61) was provided which consists primarily of four elements as follows: A 2-volt dry-cell source of potential, potentiometer *A* of the photo-electric device, potentiometer *B* of the output wattmeter and the galvanometer device, complete with contacts *R* and *L*.   These elements, together with the intervening resistors, calibrating resistor and the damping resistor *C*, form a circuit similar to the Wheatstone bridge.   The precision potentiometer *A* is geared to the carriage of the photo-electric device in such a manner that the angular variations of the potentiometer are proportional to the variation of the instantaneous ordinates under the curve on the strip chart.

The resistance of potentiometer *A* is balanced in the bridge circuit against the resistance of a similar precision potentiometer *B* located near and geared to the movable-pen carriage of a graphic wattmeter.   The latter potentiometer varies in proportion to the power output of the generator, and thus unbalance exists in the bridge circuit when the instantaneous ordinate of the graphic wattmeter is not equal to the instantaneous ordinate of the master chart.   For example, if the photo-electric device changes position in following the curve, the sliding contact of potentiometer *A* moves and unbalances the bridge, and the sliding contact of wattmeter potentiometer *B* must then move an equal amount in the same direction in order to bring the bridge again in balance.

Unbalance in the bridge circuit is translated by the galvanometer device (Galv. in Fig. 61) into periodic impulses to a motor on the gate limit mechanism of the waterwheel governor and causes the waterwheel gates to open or close to bring the power output to the value indicated by the chart and balance the bridge circuit. This bridge circuit, by modifications not shown in the figures, also originates indications, which by means of the automatic control panels start and stop the generator.   To provide for irregular stream flow at the hydroplant, float switches have been provided to cause the generator to operate at full load when the reservoir is full and water is likely to be wasted and to prevent the opera-

tion of the generator when the water level is too low for satisfactory operation. *These are independent and supersede the indications of the photo-electric device.*

The Photocell as a Light Amplifier.—One important use is the light-amplifying possibilities of the photocell. A small amount of light will change appreciably the voltage input to the grid of an amplifier or controlled rectifier. These tubes may in turn control a vast quantity of illumination.

There is another important use implying amplification. A very minute electrical, physical, or chemical change may be measured by means of a sensitive current meter, a micrometer, or a chemical indicator. This change may be so small as not to affect a rugged instrument or to perform some control function. But if this indicator will carry a small mirror, it can be made to reflect a beam of light into a photocell which will in turn control an amplifier and the final control or measurement is thereby effected.

For example, a very minute current can be made to deflect a sensitive galvanometer. Miles away may be a rugged instrument whose deflections will synchronize perfectly with the current changes—which may be produced by a temperature change, an elongation of a physical object, or a chemical change producing a variation in color.

It is of vast importance that a beam of light can connect rugged and powerful apparatus with almost infinitely sensitive equipment registering infinitesimally small changes without affecting those changes in the least degree.

The beam of light may be of any desired intensity so that the output of the phototube can be many volts. This voltage can be made to operate the grid of a vacuum-tube amplifier in whose output will appear the amplified current, or to operate the grid of a relay in whose plate circuit may be kilowatts of power.

In this case the phototube acts as a current amplifier through the medium of a beam of light.

An amplifier of this nature has been commercialized by the Allen B. Dumont Laboratories. The current to be measured, which may come from a low-impedance source such as a thermocouple, actuates a torsion string galvanometer which has an internal resistance of 10 ohms and a current sensitivity of 4×10^{-7}. The time required for full deflection is about $\frac{1}{50}$ sec.

The image of the spiral of an incandescent light is formed by a lens in the projector on the small mirror of the galvanometer system. Adjacent to the lens is a diaphragm whose aperture is the same shape as the active surface of a photocell. The lens also forms an image of this aperture.

Deflection of the mirror on the galvanometer varies the light falling on the photocell which is connected to an electron-tube amplifier with a gain of 800 times. A second stage of amplification is provided which gives a resultant gain of 4,800 times.

A Photo-electric Recorder.[1]—The light amplifier principle is utilized in a photo-electric recorder (General Electric) the basic principle of which is as follows: A measuring instrument, say a galvanometer, carries a mirror, which reflects light into one of two phototubes depending upon the direction of the deflection of this mirror. Thus minute currents cause the galvanometer to change the position of the mirror, a known amount for a known quantity of current, or other variable factor. This circuit is also employed in telemetering as well as for control.

By means of the phototubes into which the light falls and an amplifier a high-torque recording instrument is actuated so that it follows the basic instrument and records its readings. The power to operate the recording instrument is obtained from an auxiliary source. The circuit is shown in Fig. 62 and is interesting in that three types of electron tubes are utilized, phototubes, a rectifier, and an amplifier.

The recorder operates in the following manner. The light from the lamp is condensed by a lens and falls upon the mirror carried by the basic measuring instrument, say a galvanometer. From this mirror it is reflected to some point on the curved mirror in Fig. 63 and thence to the mirror of the recording meter and thence to the light-dividing reflector. If the recording mirror and the basic mirror are properly in step, the light divides equally between the two phototubes and there is no motion of the recording element.

If, however, more light enters one phototube than enters the other due to the two mirrors being out of step, either the rectifier current or the amplifier current predominates through the

[1] LaPierre, C. W., Trans. *Am. Inst. Elec. Eng.*, vol. 51, March, 1932, and *Gen. Elec. Rev.*, vol. 36, June, 1933. On telemetering see also De Croce, G., *Elec. J.*, June, 1933; and Oman, Carl, *Elec. J.*, August, 1934.

recording element with corresponding motion as the result. When properly balanced, the two mirrors in step, the rectifier current and the amplifier current are equal, and no motion occurs.
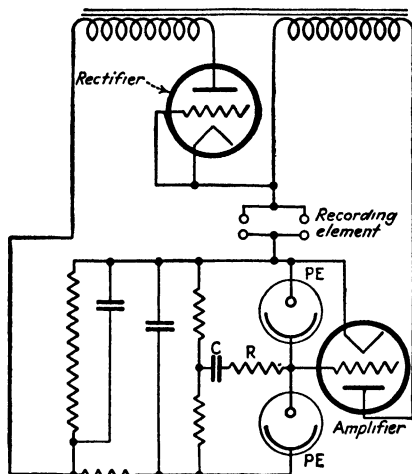
Fig. 62.—Recorder using phototubes, rectifier, and high-vacuum amplifier.

The capacity and resistance in the grid circuit of the amplifier prevent any tendency to "hunt" because of the appreciable time required to charge and discharge the condenser thereby acting as a damping element. The resistance prevents oscillation.
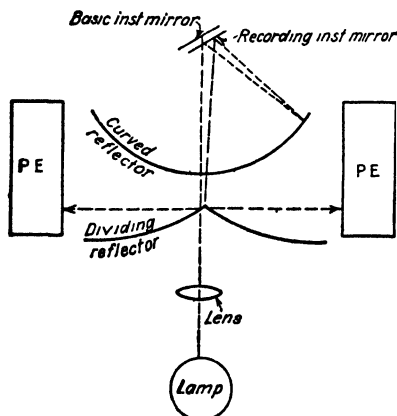
Fig. 63.—Optical system of recorder of Fig. 62.

The instrument has been used to record frequency variations of small order on transmission circuits, to record full scale less than 4 μa of current when the instrument drew less than 0.015 microwatt from the circuit under measurement, temperature where other instruments were unsuitable—for example, at high speed or high sensitivity—continuous gaging of ball-bearing diameters, strip thicknesses, and wire diameters; recording light intensity (daylight), vibration, etc.

Photo-electrically Balanced Recording Potentiometer.—In a recorder-controller developed by the C. J. Tagliabue Manufacturing Company a sensitive mirror galvanometer is the primary controlling element in which an inertialess beam of light takes the place of the customary metal boom or pointer.   The beam of light from the galvanometer to a photocell is interrupted by right and left shutters operated in synchronism with electric contacts in an electromagnetic circuit through which in turn are operated the moving contact of the Wheatstone bridge or potentiometer, and the recording and controlling mechanisms.   The photocell is not a calibrated element but serves only to detect the direction of the light beam and bring the galvanometer to zero deflection, according to the well-known null method of balancing an electric circuit.   The instrument, therefore, is not a "photo-electric potentiometer," in the sense that a balance of photo-electric currents is implied.

The galvanometer is free at all times from mechanical engagement, and this fact together with its low moment of inertia permits rapid balancing and control actions.   Furthermore, a high current sensitivity is available, permitting the use of high resistance or of very long thermocouple leads without material loss of accuracy in balancing.   Or, on occasion a very low scale range does not require a very low resistance and the resultant disadvantages.   The galvanometer is completely inclosed.   A special feature is its platinum-gold alloy suspension of particularly high tensile strength.

The recording and commutating mechanism of the device serves, in a recorder, to turn the multiple switch, depress the stylus wheel mounted on the contact carriage, and occasionally connect in a standard cell.   The mechanism is locked inactive while the contact carriage is traveling in one step from one recorded temperature to the next, and is released by the opening of an electromagnet.   Fifteen seconds after this a record is made and the switch and stylus wheel turned.   During these 15 sec., ten or fewer short steps are taken as needed, to bring the contact accurately to the balance point.   Once in every 120 records (30 to 60 min.) a switch disconnects the thermocouples and connects the standard cell, forcing the mechanism to record the standard current.   Thus, not only is the condition of the battery apparent at all times, but small corrections can be made without

readjustment of the current. The standard instrument is wired for 12 thermocouples with convenient means for connecting any number less than this. A cycle of 12 temperatures is ordinarily completed in about 5 min., but for special purposes, with some limitations as to spread of the temperatures, this time can be reduced to 3 and even 2 min.

The charts are 11 in. wide with a 10-in. scale and are rerolled at a standard rate of 1 in. per hour, to last for 60 days. The speed is readily changed to 2, 3, 4, or 6 in. per hour. The drive is synchronous, the recorder being designed for use only with alternating current.

Seismographic Recorder.[1]—There are, in general, two types of methods of recording seismic motion, photographic and mechanical. There are advantages to both methods, but by means of a phototube and amplifier Wolfe seems to have secured the advantages of both methods in the same instrument. By it the pen writer follows the angular deflections of a rotating mirror used in photographic recorders and thereby produces an ink record such as is ordinarily produced by mechanical recorders. The apparatus operates as follows:

Light reflected from the revolving mirror associated with any photographically recording seismograph with suitable characteristic excites a phototube. The optical arrangement is such that the quantity of light entering the cell is very nearly proportional to the angular deflection of the mirror. The cell circuit is coupled through resistances to a push-pull amplifier, the output of which goes to a large galvanometer whose rotating element carries two coils. The plate current of one tube in the output stage flows through one coil; that of the other tube through the other coil. With no input potential to the amplifier the direct currents through the two coils exert equal and opposite torques, and the rotating element is held at zero position. However, if we assume an alternating potential input, representing deflections of the rotating mirror, we obtain alternating currents in the coils that are 180 deg. out of phase. The resultant torques, being in phase, produce deflections of the rotating element. A pen attached to the latter records the motion on a revolving drum in the usual manner.

[1] WOLFE, HALLEY, *Rev. Sci. Instruments*, p. 359, October, 1934.

High-speed Potentiometer.—A potentiometer circuit, with electronic balancing mechanism having high speed and operating a primary galvanometer under conditions permitting high sensitivity has been described by Gilbert.[1] Here a variable indicating current is passed through a fixed resistance with the *IR* drop developed opposing the unknown e.m.f. For all conditions of potentiometer balance the indicating current is in a direct proportion to the unknown e.m.f. The indication of the milliammeter may be calibrated in terms of the input.
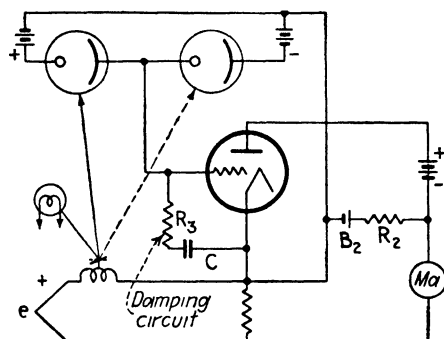
Fig. 64.—Gilbert's high-speed potentiometer.

A mirror deflects a beam of light into one or the other of two phototubes by means of a prism. The phototubes are in a bridge as shown. The network B_2R_2 is a balancing circuit to avoid the portion of the tube characteristic near cut-off. CR_3 is a damping circuit.

With a 10-ohm galvanometer, a voltage of 10^{-5} volt will cause a response, and a 1,000-ohm galvanometer will respond to 10^{-8} ampere.

Phototubes with Split Cathodes.—Clark Instrument Company has constructed cells in which the cathode is in two (or more) portions, with an insulating material between. Thus a slight movement of the light beam will cause current to flow from one or the other of the two halves of the tube. Wein has constructed tubes with 4-sectioned cathodes. By illuminating such tubes with a moving beam a current of various wave forms could be produced, useful for laboratory. Other uses have been made of split-cathode phototubes.

[1] GILBERT, R. W., High-speed, High-sensitivity Photoelectric Potentiometer, *Rev. Sci. Instruments*, January, 1936.

Photo-electric Color-measuring Equipment.—Application of light-sensitive devices to the measurement not only of light intensity but of color is natural, and has been rapid. There are in general three types of color-measuring instruments. Color analyzers[1] give complete information about the color of a sample because they produce a curve of reflection or transmission coefficients versus wave length. These curves constitute a mathematical, unchanging definition of a color and can therefore be used to great advantage in cataloging, specifying, and mixing dyes, paints, inks, etc.

Color comparators determine whether a visual color match exists between two samples.

One-variable instruments measure or compare a single optical property of a material or substance.

Photo-electric methods of color measurement have the advantages of: (1) speed of observations, (2) lack of eye fatigue, (3) no necessity of a trained observer, (4) full sensitivity at end regions of visible spectrum, (5) no necessity of darkening room during observations. These advantages are combined with the fact that a well-designed photo-electric instrument is as accurate as any other type instrument, or more so.

The General Electric recording color analyzer is a good example of this class of instrument. It automatically plots a continuous color curve on a liquid or solid sample for the visible range, 4,000 to 7,000 angstroms, in about $3\frac{1}{2}$ minutes. It is accurate enough to check with Bureau of Standards data on a color filter and is constant enough to retrace a curve on a sample without appreciable widening of the pen line. It represents a modification of an instrument first developed by A. C. Hardy[2] to obtain a reflection curve. One-half of a collimated beam of monochromatic light is intercepted by a right prism and sent to the sample. The light reflected from the sample then goes to a flicker disk. The other half-beam, not intercepted by the right prism, goes to the flicker disk through a shutter. This flicker disk has its solid sectors coated with a standard white pigment and is so situated with respect to a photocell that, as it revolves, the cell alternately receives one beam reflected from the sample

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[1] See NEUSTADT, HERBERT, *Electronics*, May, 1933, p. 128, for a description of devices in the American market.

[2] *J. Optical Soc. Am.*, vol. 18, pp. 96–117, 1929.

through the open sectors of the wheel, and then receives the other reflected from the standard white solid sectors. The alternations occur 60 times per second. If the two beams differ in intensity, the cell output will be a 60-cycle pulsating current. The a.c. component of this output is applied through an amplifier and is fed from an independent 60-cycle source. When the cell receives a more intense beam from the standard than from the sample, the motor will be driven in one direction; when it receives a less intense one, the motor will reverse; and when it receives equal intensities, the motor will stop. By causing the motor to operate the shutter which regulates the amount of light reaching
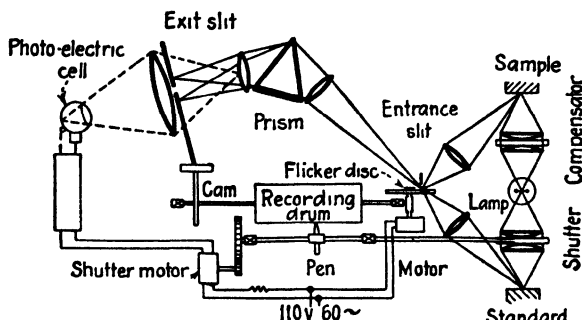
Fig. 65.—Color analyzer. (*After Hardy*)

the standard white sectors, the two beams are automatically balanced. A pen records the position of the shutter on a rotating drum. The same drive that rotates the drum also varies the wave length of the monochromatic light at a uniform rate from 4,000 to 7,000 angstroms. The resultant curve shows how much light reflected from the standard was equal to the amount of light reflected from the sample for every wave length in the range. It therefore gives the reflection coefficients of the sample as percentages of those of the standard. If absolute coefficients are desired, correction factors may be applied.

The American Photoelectric Corporation has developed a spectrophotometer which is built by Eimer and Amend. There are three modifications of the instrument, one to give transmission curves in the visible spectrum, another to give reflection curves, and the third to determine relative energy distribution in the ultra-violet. Each instrument essentially consists of (1) a carrier for the sample, (2) a light source, (3) a spectrometer to

segregate the lines or bands of the desired wave lengths, (4) the case containing the photocell unit, electrical circuits, amplifiers, control panel, etc., (5) a galvanometer, and (6) a Wheatstone bridge, usually one of the Kohlrausch type.[1]

In obtaining a curve, the wave-length setting is made and then a circuit is balanced twice, first, without the sample, and then with the sample inserted. The desired coefficient is then read from a dial directly calibrated in absolute percentages. A curve can be drawn from a sufficient number of such readings, each reading requiring from 15 to 20 sec.

Different types of light sources and photocells and different makes of galvanometers, bridges, and spectrometers can be used without affecting the readings more than 0.1 per cent.

A modification of the instrument, useful in pyrometry, will detect changes as small as 1° in the temperature of a material under heat treatment.

A Manual Spectrophotometer.—A device intended for making spectral reflectance and transmission measurements on a variety of materials has been developed by General Electric. It consists essentially of two parts: monochromator and photo-electric photometer.

The monochromator is a double-prism type which insures a high degree of purity. The slits are of the bilateral type and automatically adjusted to pass a 10-millimicron wave-length band for each wave-length setting. The selection of wave length is made by moving the mirror normally to its surface. The value of wave length is indicated directly from 400 to 700 millimicrons.

The photometer combines the polarization method of photometry with a manually adjusted photo-electric balancing scheme in such a manner as to eliminate from the measurement the factor of light-source characteristic, phototube and amplifier sensitivity. Reflectance values are expressed in percentage of the standard selected by the operator. Transmission is expressed either directly or in percentage of a standard transmission specimen.

Light from slit 3 is plane polarized by rochon 1. The Wollaston prism gives two components mutually perpendicularly polarized which reach the sample and standard, respectively.

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[1] Photoelectric Spectrophotometer, *Instruments*, February, 1930.

Rochon 1 is mounted on a bearing and is rotated by a cam arrangement. The angular position of this rochon determines the ratio of energy distribution in the two beams and is a measure of the coefficient of reflectance of the sample in terms of the standard. Rochon 2 is mounted in the hollow shaft of a synchronous motor which runs at 1,800 r.p.m. The rotation of this element serves to vary the light intensity of incident beams from minimum to maximum on the sample and standard out of phase with each other. A phototube views a frosted glass
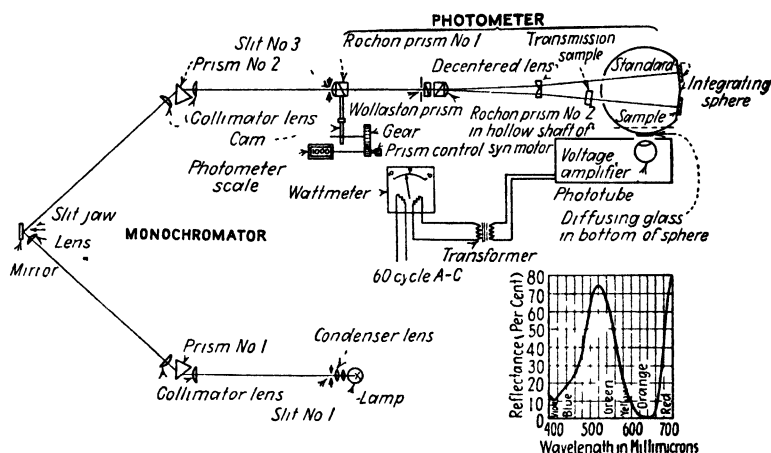
Fig. 66.—Schematic of manual photo-electric spectrophotometer. Typical record showing transmission through green cellophane.

in the sphere wall, the brightness of which is a function of the sum of the product of beam intensity and reflectance for both sample and standard, but when the light reflected from the standard and sample is not equal, an alternating component is present in the phototube current. The phase of this alternating component determines which of the two beams is more intense. This amplified component is impressed upon the voltage coil of the wattmeter, whose current coil is fed from the same power supply used to drive the synchronous motor. Rochon 1 is then manually adjusted until the wattmeter indicates zero. The angular position of the rochon 1 is then a measure of the reflection coefficient of the sample in terms of the standard.

The illumination on the sample and standard is normal to the surfaces and covers a portion 1 in. in diameter. The frosted

glass in the integrating sphere wall is symmetrically located with respect to sample and standard positions. Transmission measurements are made by using similar samples in the standard and sample reflectance positions and introducing the transmission specimen in the incident sample beam.

The light incident on the sample and standard is derived from the same source, thus eliminating the characteristic of the source in measurements. Furthermore, the optical system with respect to the sample and standard is common, with the exception of a pair of decentered lenses, which are used to obtain wider angular deviation of sample and standard beams. Since the voltage amplifier amplifies alike the current due to light from sample and standard, the measurement is independent of the characteristic of this unit. Only monochromatic light reaches the phototube; thus the spectral response characteristic of the phototube does not enter into the result.

Rochon 1 is actuated by a cam so that the photometer may read directly in percentage of the standard selected by the operator. Provision is allowed for the addition of other cams later for special functions.

In an automatic version of this instrument,[1] the alternating component is not passed to a wattmeter to be determined visually as to its order of magnitude and direction but is used to control the direction of rotation of a balance motor by means of grid-controlled rectifiers which thereby readjust rochon prism 1 to obtain a redistribution of energy in sample and standard beams. The position of this prism is then a measure of the desired quantities. In this variation the device can be made to plot its own curve by moving a sheet of coordinate paper according to a wave-length scale at the same time that a pen indicates the angular position of rochon prism 1.

Color Comparators.—In operation, color comparators determine whether two samples reflect or transmit equal percentages of incident light. Their function, the detection of visual color matches, is accomplished by making four observations: one with white light, and the three others with the three primary colors. A nonmatch can sometimes be detected under white light, that is, the cell will not receive equal amounts of light from the two samples. But if it does, there is not yet any assurance that a

[1] See *Electronics*, March, 1936, p. 17.

good match exists.   However, if the two samples reflect or trans-
mit equal amounts of red, green, and blue light to the cell,
they will appear to the eye to have the same color under all
ordinary illuminations.   In the comparators described here,
tricolored filters are provided for making matches in this way.
Their use is also helpful in correcting differences in color.   Know-
ing in what portion of the spectrum the difference lies, it is possi-
ble to make an estimate of what colors should be added to one
sample to make it match the other.

The Colorscope (manufactured by the Sheldon Electric Cor-
poration[1]) finds its widest use in the textile industry because it is
especially adapted to the measurement of Fadometer and
Launderometer results and to the correction of misdyes.   It is a
bridge, two arms of which are matched photocells.   The samples
are placed in holders which rotate them, and the photocells see
these rotating samples by indirectly reflected light.   This
feature avoids error which the effect of weave, texture, or sheen
might cause and allows such comparisons as wool with silk, or
glossy paper with a rough sheet, on a color basis alone.

As the samples are rotated, the operator balances the bridge by
varying a resistance until the galvanometer reads zero.   Then
the samples are interchanged in position before the photocells
and rotated again.   Any resultant meter deflection shows that
the bridge is no longer balanced and that one sample is redder,
or bluer, etc., than the other.   Because the method of obtaining
balance makes these deflections proportional to difference in
color alone, the meter is calibrated to give percentage differences.

This feature gives the instrument certain advantages.   It
permits the matching of dull dark surfaces with the same precision
as light ones.   It also allows the operator to select some small
percentage as a tolerance and use it throughout, regardless of
depth of color.   And the direct calibration in percentage gives
quantitative information for the correction of misdyes.

Standard tiles are provided with the instrument for checking
it each day, and a sensitivity control is used to correct any
variations in the photocells.

The General Electric color comparator utilizes a photocell and
amplifier, but in this case there is a bridge, one arm of which
contains the plate circuit of the last amplifying tube.   The

[1] See U. S. Patent 1,834,905.

method in use is that of balancing the bridge with the standard in place and then inserting the sample. Its accuracy is as good as that of the eye in all matches and better in the end regions. It is not calibrated because its sensitivity depends on the photocell. However, the operator can set his own tolerances for each material and check them from time to time.

A set of gray reflection standards comes with the instrument for the purpose of checking and estimating sensitivity.

American Photoelectric[1] makes two instruments which match the total transmission of similarly colored liquids. One of these instruments, the advanced model, contains a bridge in which two arms are photocells. It can be used as a comparator or as a turbidity meter. When used as a comparator, the bridge is balanced with the standard and the sample each viewed by a photocell in the bridge. Interchanging them will then show if they match to 0.05 per cent.

As a turbidity meter, the instrument uses the Tyndall beam method and so gives values directly only when the size and concentration of suspended particles are small. But its range can be extended by interpolation between readings on similar solutions of known concentration. Readings are obtained in one or two minutes and are claimed to be more accurate than those usually obtained by evaporation. The other A.P.C. comparator contains one photocell in a bridge and matches total transmission less precisely than the advanced model.

Total reflection factors can be measured by a third A.P.C. instrument, useful in the textile and paper industries because it also measures opacity and translucency. In measuring total reflections with this instrument the standard is illuminated by a normal beam of collimated light and viewed by two photocells at 30 deg. from the surface. The output of these cells goes to a galvanometer and opposes the output of a third cell which receives light directly from the source. The galvanometer is brought to zero reading by a variable resistance and then the standard is replaced by the sample. This time the galvanometer is brought to zero by a slide wire which is calibrated to give directly the reflection factor of the sample as a percentage of that of the standard.

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[1] See *Instruments*, February, 1930.

Measuring Opacity and Turbidity.—Opacity is defined as the ratio of a material's reflection coefficient when backed by a nonselective black body to that when it is backed by a nonselective white body. To measure opacity with this instrument, therefore, observations are made first with the sample backed by a block of chalk, and then with it backed by a box whose inner
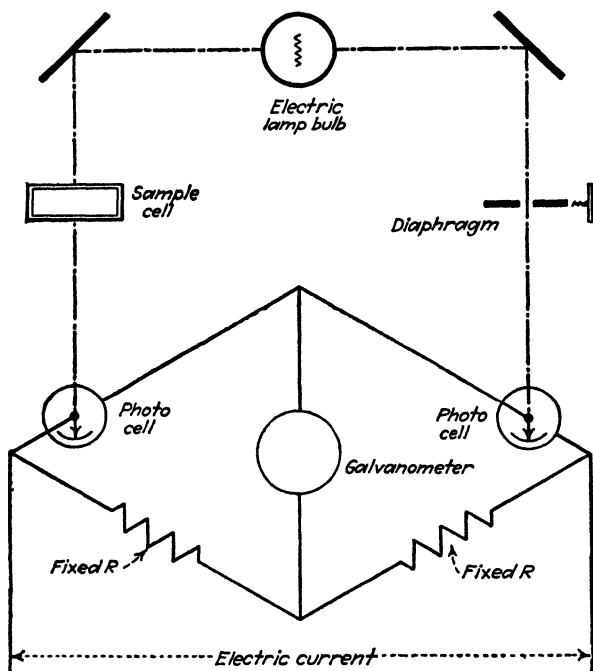
Fig. 67.—Exton Scopometer (*Bausch and Lomb*) for measuring turbidity of liquids.

surface is mat black. Translucency, being defined as one (unity) minus opacity, is easily derived.

The Exton Scopometer of Bausch and Lomb is a one-variable instrument designed to measure turbidities or total transmission of any liquid. It is most used in making blood tests. Referring to the figure, aperture of the diaphragm is varied by a micrometer screw until the galvanometer reads zero and the reading taken from a turns-counter on the screw.

Zeiss Recording Photometer.—This is a one-variable instrument for obtaining intensity analyses of photographically

recorded spectra. A negative on which the spectral lines have been recorded is moved at a uniform rate between a light source and a photocell. Photocell current produces a voltage drop along a fixed resistance; this is applied to a Wolff single-thread electrometer. The position of the thread is recorded on a moving photographic plate the result being a continuous intensity curve. The plate may be made to move up to 500 times as fast as the object, thus showing up details. The sensitivity is controlled by varying the lamp voltage; provision is made for watching the electrometer thread during operation.

Cambridge Recording Microphotometer.—The Cambridge Instrument Company has developed a photo-electric recording microphotometer for measuring the distribution of energy in stellar and solar spectrum lines, etc. The instrument will be found described in *Monthly Notices* of the Royal Astronomical Society, vol. 91, No. 1, and in a bulletin of the manufacturers by Professor J. A. Carroll and E. B. Moss.

Photo-electric Reflectometer.—An instrument which measures the reflectance, opacity, and color of paints, papers, pigments, powders, ceramic products, textiles and chemicals is a photo-electric adaptation of the Hunter Visual Reflectometer.[1] It uses a null method which makes it possible to operate directly from ordinary current supply. Test surface and comparison surface, at opposite ends of a light tunnel, are illuminated by a single lamp movable between them. Each of two rectifier-type photocells receives light reflected at an average of 45 deg. from one of the surfaces. A galvanometer indicates unbalance of cell outputs. The reflectance scale moves with the lamp past a stationary indicator. To determine reflectances, a standard is first placed in the test end of the instrument, and the lamp moved to the position for which the scale reading gives the reflectance value of the standard. By means of a compensating shutter, the light falling on one or the other of the photocells is then reduced until the galvanometer reads zero. With instrument thus adjusted, unknown surfaces may be substituted for the standard, and their reflectances measured directly. To obtain color values, reflectances in colored light are determined. The instrument is made by the Henry A. Gardner Laboratory, Washington, D. C.

[1] *Instruments*, October, 1934, p. 219.

Comparator.—Recently a new type of spectroscopic comparator has been developed by Prof. George R. Harrison, director of the Spectroscopy Laboratory, Massachusetts Institute of Technology. A photocell which takes the place of the eye of the operator can make measurements ten times as fast as the conventional method, and the results are twice as accurate. In the new machine a beam of light is made to pass through the photographic plate, and this beam actuates a photocell amplifier system. When the instrument is set on the peak of a spectrum line, the photocell operates a grid-controlled rectifier and flashes a mercury arc. The light from the arc photographs the reading of the wave length on a moving film.

With the use of these readings the spectroscopist can identify the spectrum lines in the picture. From these lines the energy levels of the substance being analyzed are calculated by a very laborious process which hitherto has been carried out on pencil and paper. A companion machine to the photocell analyzer is the interval sorter which makes the mathematical computation automatically. The interval sorter or mathematical machine has the amazing capacity of 50,000 subtractions per minute, at the same time recording the results photographically. By the use of these two machines it has been possible to speed up greatly the application of spectroscopic analysis, a science that is proving of great value in physics, chemistry, metallurgy, astronomy, and even medicine.

Razek-Mulder Color Analyzer.—This instrument built by the Thwing Instrument Company is an automatic recording and indicating spectrophotometer. The illuminating unit is a nearly hemispherical aluminum reflector in which are mounted twelve 15-cp. bulbs distributed uniformly. The top of the hemisphere is a plane surface blackened on the inside and has a small opening at its center over which the standard or sample may be placed. Light which is reflected normally from the surface covering the opening goes through a chimney, whose interior is blackened, to the entrance slit of a spectrometer. The spectrometer breaks up this light and sends a band of wave lengths 10 millimicrons wide to a photocell. The photocell output is amplified by one tube and goes to a galvanometer. A beam of light from the galvanometer mirror is focused on the plane of a photograph film and part of it is reflected by a mirror to the visual scale on

the front panel.   When the crank on the front panel is rotated, a mirror in the spectroscope is turned so as to vary the wave length of light which comes through the exit slit and falls on the photocell.   This crank also moves the film so that the light spot is recorded on it as a curve of reflection coefficient versus wave length.

In taking curves, a run is first made on a block of $MgCO_3$ to obtain a standard of reference and then one is made on the sample. If it is desired to record curves on a number of samples on the
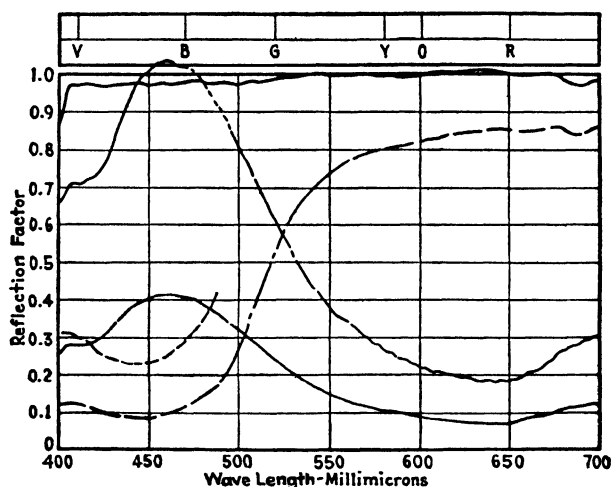
FIG. 68.—Example of Razek-Mulder color analysis.

same film, there is a device which can be used to make some of the curves be recorded as dotted lines for the sake of easy distinction between close curves.   For very dark samples, the observer may use a second galvanometer which can be made two and a half or five times as sensitive as the one for normal use. After the curves have been taken, a light is switched on that prints coordinates and an identification number on the film. The film is then ready for development.

The accuracy of the instrument depends on linearity of galvanometer response to intensity of light falling on the photocell. This linearity is assured by the spectrometer slits which automatically compensate for the photocell characteristic and keep the wave-length band width at 10 millimicrons.   Tests have shown that this linearity holds good for intensity values from

· zero to three or four times the maximum value used in the instrument. Accuracy also depends on the constancy of voltage supplied to the illuminating lamps. A voltmeter is mounted on the front panel and shows any variations in illuminating voltage. A light spot from a mirror mounted on another voltmeter also records on the film the voltage at which the curves were taken. Surface gloss is another factor which might disturb the accuracy of the measurement of color, but that is practically eliminated by the method of illumination.

A curve can be taken in about ten seconds and coordinates recorded in less than five. Allowing two minutes for developing and preliminary fixing of the film, a curve on a sample is ready for inspection in less than three minutes after starting the operation. This curve can be read to 0.5 per cent.

For methods of color analysis using photocells see MULDER, P., and J. RAZEK, A Portable Recording and Indicating Color Analyzer, *J. Optical Soc. Am.*, vol. 20, pp. 155–156, April, 1930; *Cotton*, vol. 91, pp. 981–983, August, 1927, for description of T. C. B. photocolorimeter designed by Toussaint.

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GIBSON, K. S., Use of Photocell in Spectrophotometry in Photoelectric Cells and their Application, a discussion at a joint meeting of the Physical and Optical Societies, 1 Lowther Gardens, Exhibition Road, South Kensington, London.

U. S. Patent 1,882,962, F. Sawford on photoelectric method of measuring thickness of paper. Patents 1,908,610; 1,933,831 *et al.* to Eastman Kodak Co. in controlling photographic printing exposure by phototubes. 1,898,219, C. H. Sharp on color matching.

MILLER, C. W., A Linear Photoelectric Densimeter, *Rev. Sci. Instruments*, April, 1935. This uses the remote cut-off feature of the 58-type tube to give a linear characteristic.

BISBEE, R. F., Color Measuring of Porcelain, *Elec. J.*, December, 1934, p. 482.

U. S. Bureau of Standards *Letter Circ.*, LC-473, "Photoelectric Colorimeters," July 9, 1936.

Photo-electric Photometry.—Numerous applications have been made of light-sensitive equipment to the problems of pho-

tometry.   In the simplest cases a phototube takes the place of
the human eye at some sort of photometer, or a phototube
may be connected directly to a battery and current-measur-
ing device such as an electrometer or galvanometer.   Light
from the lamp to be tested is allowed to fall on the phototube
and a reading of the current is made.   Vacuum cells are linear
with respect to their current versus illumination characteristics
and therefore may be calibrated at several points by means of
standard sources.

The currents obtainable from vacuum cells are so small they
need to be amplified before very accurate or stable methods of
measurements are possible.   A simple circuit consisting merely
of a phototube connected to an
amplifier is shown in Fig. 69
(Westinghouse Lamp Com-
pany).   With the cell dark, the
resistances are adjusted so that
the milliammeter reads zero.
Then the phototube is exposed
to the illumination from a
standard lamp at a fixed dis-
tance and the reading of plate
current is noted.   Next the
unknown lamp is permitted to illuminate the phototube and
the distance between this lamp and the phototube is adjusted
until the same plate-current reading is noted.   Then the relative
illumination of the two sources may easily be calculated.   In
some cases an iris diaphragm is interposed between the cell and
the lamp to avoid the difficulty of moving the unknown lamp
back and forth until the desired plate current is reached.

Fig. 69.—Simple use of phototube in photometry.

Such a circuit suffers from the fact that the response from a
given lamp is a function of the amplifier tube, the phototube,
and the voltages involved.   It is a convenient, speedy method
and simple to operate.

A circuit which eliminates the characteristic of the amplifier
tubes has been developed and widely used by the Electrical
Testing Laboratories.   The circuit is shown in Fig. 70.   It is
essentially a null method.   With the cell dark, the bias of the
first amplifier is made zero.   Then the bias of the second tube is
adjusted until the bridge is balanced.   When the phototube is

illuminated the bridge is unbalanced; the unbalance current is a measure of the illumination. In practice the bridge is brought back to balance by adjusting the bias of the second tube. The voltage required to rebalance the bridge is calibrated in candle power, or lumens. The similarity between the circuit and an amplifier-tube voltmeter will be apparent to the reader who has noted the voltmeter circuits in Chapter III. In this case the
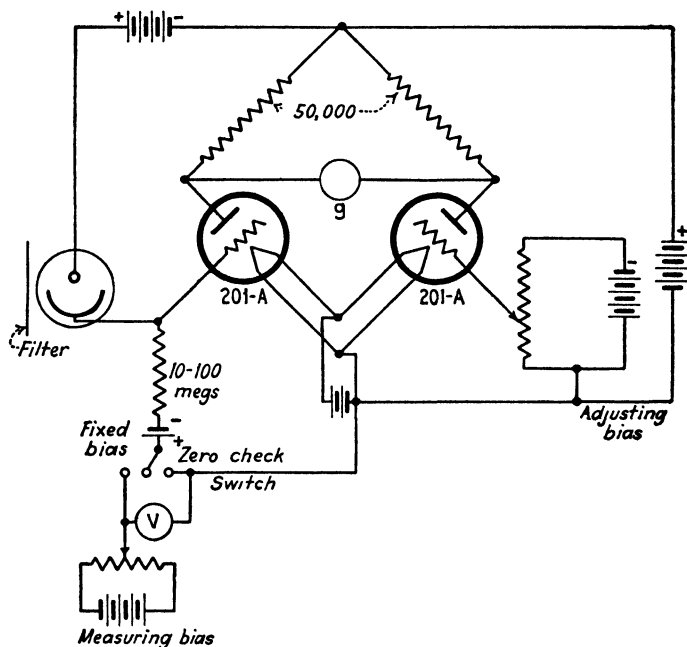
FIG. 70.—Photometry circuit in which variable factors due to amplifiers are balanced out.

phototube current flowing through the resistor between grid and cathode affects the bias on the first tube. This grid resistor, being of high value and therefore quickly affecting the balance of the bridge, must be stable and constant in value. The phototubes should be linear; other small variations in the circuit will not appreciably affect the readings, for example, small changes in filament voltages.

A third circuit, also from Electrical Testing Laboratories, which involves neither the linearity of cell nor the amplifier is shown in Fig. 70. The lamp under test and a comparison lamp, on a

track graduated in photometric units, are permitted to shine alternately upon the phototube. This is accomplished by means of a rotating glass disk one-half of which is silvered; the other half is clear. The light from the comparison lamp shines through the disk, that from the test lamp is reflected into the photocell. A contactor is rotated in synchronism with the disk. This
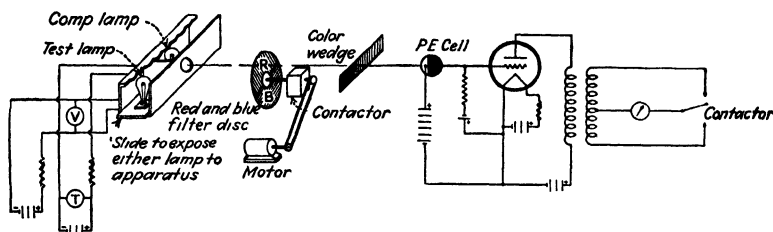
Fɪɢ. 71 —Circuit eliminating necessity of linearity in tube or photocell.

contactor acts as a switch to throw the galvanometer into either one or the other of the two secondary windings on the output transformer. Thus, when the test lamp reads less than the comparison lamp, the galvanometer reads in one direction; and it reads in the opposite direction if the test lamp has a greater output than the standard.
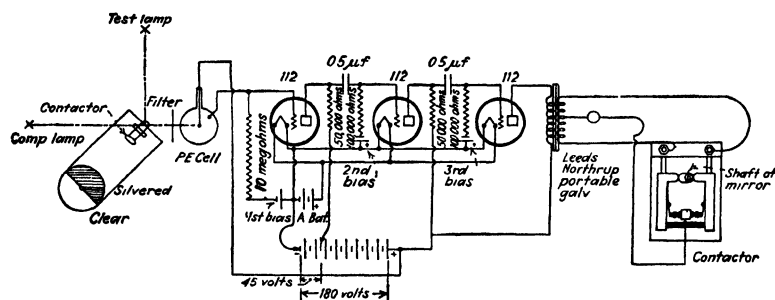
Fɪɢ. 72.—Photo-electric photometer using rotating mirror and amplifier.

In this case the photocell and amplifier perform no other function than the eye with an ordinary photometer. Thus, any variations in, or lack of, linearity in the circuits or apparatus do not appear in the final result.

Sharp uses a modification of this circuit to measure the color temperature of lamps. The light shines through a red- and blue-sectored disk which rotates in the path. By interposing a color

wedge in the path an adjustment is found where both components are equal. Now the comparison lamp may be substituted for the unknown and its temperature varied until the same, or zero, reading on the output galvanometer is secured.[1]

A Sensitive Light-intensity Indicator.[2]—Figure 73 shows a sensitive photo-amplifier circuit which can be used for accurately matching the intensities of amounts of light. With this circuit
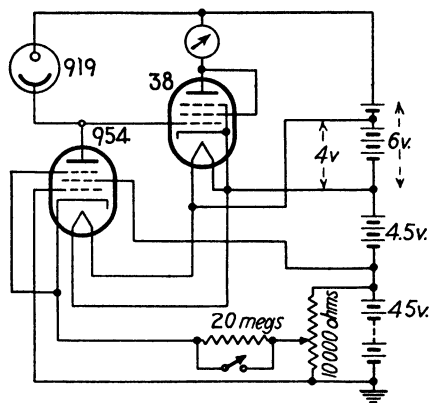
FIG. 73.—Light-intensity indicator of Shepard.

it is possible to indicate easily light differences or changes which may amount to small parts of 1 per cent. In this circuit arrangement the high-impedance 954 pentode acts as a load impedance for the 919 high-impedance vacuum-type phototube. The potential of the common connection between the 919 and the 954 is determined by the intersection of the 954 and 919 characteristics. A small change of light on the phototube will result in an output of several volts. This output voltage is applied to the grid of a 38 tube the plate current of which is indicated on a 200-ma. meter. As the phototube with the 954 load has an extremely high output impedance, it is necessary

[1] Other applications of the phototube to photometry may be found in Zworykin and Wilson, Photocells and Their Applications; Campbell and Ritchie, Photoelectric Cells, in the *Gen. Elec. J.* (British) August, 1932, pp. 149–156; in various *Trans. Illum. Eng. Soc.;* and in "Photoelectric Phenomena," Hughes and Du Bridge. See also GHEORGHIN, T. D., Gas-filled Photoelectric Cells in Photometry, *Ann. Physik*, vol. 20, pp. 133–242, September, 1933. (Uses two phototubes and two electrometers one cell to maintain the source constant.)

[2] SHEPARD, F. H. JR., I. R. E. Convention, May, 1936.

to operate the 38 so that its grid-input impedance is extremely high. To reduce the grid emission to a minimum, the voltage to the heaters of the 38 and the 954 is reduced to 4 volts. The possibility of emission from the heaters to the grid is eliminated by operating the heaters at a potential positive with respect to the plate of the 954 and the grid of the 38. Gas current to the grid of the 38 is kept at a minimum by keeping the potentials within the 38 low to minimize the ionization of any gas that may be in the tube. As all of the high-impedance external connections are made to electrodes brought out to the tops of
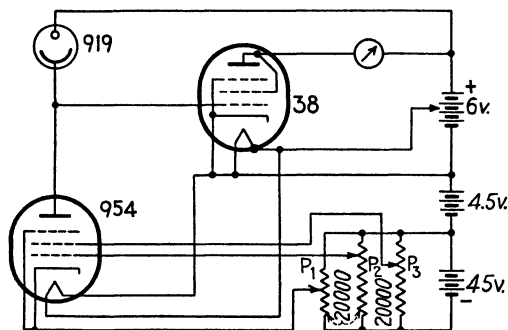
Fig. 74.—Light-variation indicator.

the tubes, external leakages are reduced to a minimum. External leakage can be greatly reduced by carefully cleaning the tubes and coating them with a nonhygroscopic wax. This can be done by dipping the tubes in hot ceresin wax and holding them under the surface of the wax until the greater part of the moisture on the glass is boiled off. Care should be taken not to scorch the wax.

Light-variation Indicator.[1]—It is sometimes desirable to reduce the sensitivity of the foregoing device to small percentage changes of light. This can be done to any desired degree by varying the plate characteristics of the 954 between that of a pentode and that of a triode. This can be done in the arrangement shown in Fig. 74, by properly adjusting P_2 and P_3 to control the relative potentials on the control and screen grids. When the No. 2 grid of the 954 is positive with respect to the cathode, the 954 has a high-impedance pentode characteristic, and changing the No. 1 grid bias changes the height of the characteristic.

[1] SHEPARD, *loc. cit.*

The 954 phototube load can be adjusted to give practically any desired positive-impedance load at any desired current 'and at any desired voltage across the tube by adjusting P_1, P_2, and P_3. This means that the full-scale reading of the output meter can be made to cover a fraction of a per cent light variation, a 100 per cent light variation, or any desired amount between these two extremes. A photo-amplifier such as this finds its application as a densitometer for use in connection with the analysis of photographically recorded spectrums or for use with a suitable monochromator or light filter as a means of measuring the absorption lines or the concentration of certain chemicals in solution. These are only two of a large number of possible applications for this type of circuit.

A Light-ratio Indicator Circuit.[1]—A device that indicates directly a ratio of the intensities of the light sources is useful for making comparisons of the light transmitted or reflected by different specimens. For instance, in color matching, the unknown samples can be set up so as to transmit or reflect light directly or indirectly to each phototube. A color filter is then placed between the light source and the samples. If a variation in the ratio is indicated by the device, it is obvious that one sample transmits or reflects more of the color in question. In this way, by putting various color filters in front of the light source, we can match the samples in any desired light bands.

Because this method indicates changes in the ratio of light, it can be used successfully to compare the color of extremely small objects with a larger standard sample by mounting the small specimen against a black background.

Figure 75 shows a circuit that will give a definite output versus light-ratio curve regardless of the actual intensities of the lights in question, provided, of course, the intensities are greater than a certain threshold value determined primarily by the leakage currents of the phototubes as affected by the dirt and moisture of the amplifier tube, as well as the leakage current of C_1 and the grid current of the first amplifier tube.

If the two phototubes are equally illuminated, the average current going into or out of C_1 over a period of time is zero. If, however, the light on one phototube is doubled, C_1 will be charged, increasing the time that the anode of this phototube is positive.

[1] SHEPARD, F. H. JR., *Proc. Radio Club Am.*, June, 1935.

The voltage across C_1 for any given light ratio will be directly proportional to the a.c. voltage supplied to the phototubes. Thus the d.c. voltage change across C_1 when the a.c. supply voltage to the phototube is known can be taken as a measure of
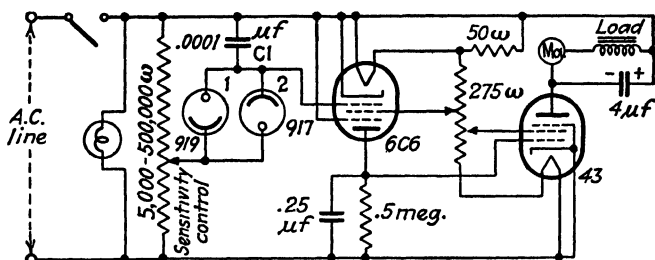
Fig 75.—Circuit for light-intensity indicator.

the light ratio.   This d.c. voltage is indicated by the d.c. amplifier (see Chap. III for this d.c. amplifier).

Photometer.—An interesting combination of electronic-voltage regulator, a vacuum-tube voltmeter, and a phototube set-up is shown in Fig. 76 from Fink.[1]   With it it is possible to compare two light intensities to an accuracy of one-tenth of 1 per cent.
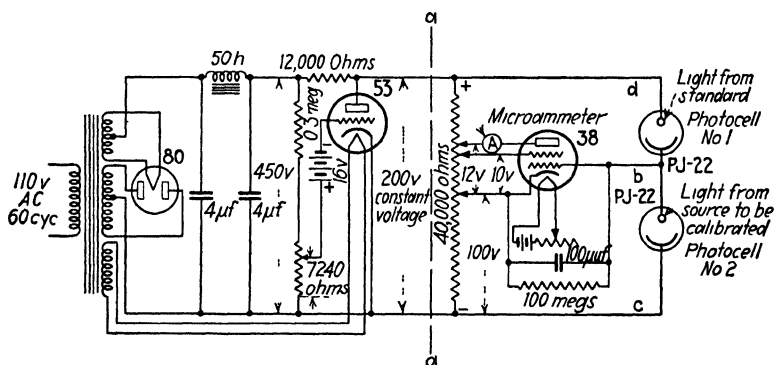
FIG. 76.—Electron-tube photometer.

The voltage regulator uses a 53 with its two sets of elements connected in parallel.

The theory of the measurement is this: If the light falling on photocell 1 is equal to that falling on cell 2, equal currents will flow in each, and the voltage applied across the two cells will

[1] FINK, D. G., *Electronics*, June, 1934.

divide equally between them. That is, the voltage between points *b* and *c* will have a definite value, very near 100 volts. Now, if the light falling on cell 1 becomes greater than that falling on cell 2, an additional current will tend to flow in cell 1. But this greater current will also have to flow in cell 2 because of the series connection; yet cell 2 is not receiving sufficient light to cause this greater current to flow. The only way in which the additional current can flow in cell 2 is this: The voltage across cell 2 must increase. As it does so, the voltage across cell 1 must decrease, and the current decreases also. The net result when more light falls upon cell 1 is only a small increase in current accompanied by a large change in the voltage distribution between the two cells. The change in voltage distribution, which can be measured by measuring the voltage across points *b* and *c*, is thus a direct indication of the division of light between the two cells.

To measure the ratio of the lights falling on the two cells, therefore, it is necessary simply to measure the voltage between points *b* and *c*.

The vacuum-tube voltmeter 38 is operated with one-half its normal heater voltage, 12 volts on the plate and 10 volts on the screen, to attain high input impedance.

The circuit is usually used in a modified photometer set-up. Each light source is arranged so that it can be moved relative to its photocell. Balance is obtained by moving the unknown source away from or nearer to its photocell while the distance between the standard and its cell is kept fixed. The ratio of the two distances, at balance, squared, is then a measure of the relative intensities of the two light sources.

Ultra-violet Recorder.—If a phototube is allowed to charge a small condenser which then discharges at a rate dependent upon the rate of charge (the phototube current), it may be used to fire a "trigger" tube, or a filamentless gaseous rectifier of the grid-controlled type. In this manner Westinghouse[1] has designed a meter that will automatically record the strength of radiation in the invisible portions of the spectrum. The number of times per minute that the trigger tube fires is noted on a continuous chart. This rate of charge and discharge is

[1] WOLF, L. J., Ultra-violet Recorder, *Electronics*, June, 1936.

dependent upon the phototube current which is determined by the intensity of the radiation.

Automatic Optical Pyrometer.—There has been a need foi a dependable pyrometer that actually measures quickly the temperature of materials in motion—*e.g.*, in steel mills, glass plants, etc. The Brown Instrument Company has such a device known as the Optimatic, which uses two phototubes connected in a Wheatstone bridge and an amplifier tube. A water-cooled telescope scans the hot body and affects one of the two photocells. Variations in temperature cause the viewing photocell to change its resistance, which changes the grid bias of the amplifier, which in turn influences the illumination of the standard lamp. This
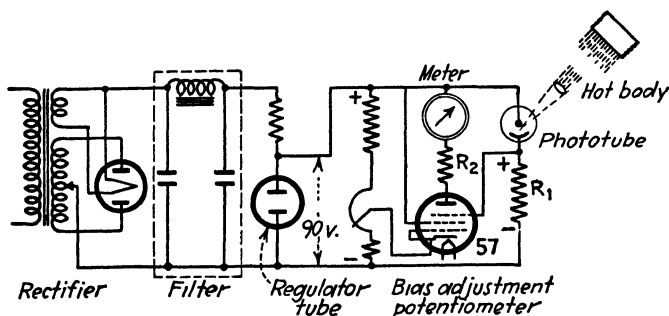
Fig. 77.—Photo-electric pyrometer circuit.

finally balances out the difference arising from the variations in light emitted by the object under measurement.

Photo-electric Pyrometer.—The phototube has been used many times to measure temperature by utilizing the radiation from the heated object. A simple circuit, shown in Fig. 77, is that of the General Electric Photo-electric Pyrometer. It has been employed in the measurement of temperature of steel billets, seamless-steel tubes, cement clinker, and material in small heat-treating furnaces. While it has not yet been employed to measure temperature of molten metal, there is no reason to believe it unsuitable for such applications.

The equipment is best suited to those applications in which it can be permanently installed at a location where continuous indication or record of temperature is desired. For example, it may be installed on a seamless tube mill to indicate or record (or both) the temperature of each tube as it comes through the mill.

In a similar manner, it may be installed to measure the temperature of successive bars, billets, etc., passing through a mill. Or it may be installed to view the hot zone in a cement kiln and provide a continuous indication and record of the cement clinker temperature. Since it is necessary to calibrate the photo-electric pyrometer with the equipment installed and the phototube located to view the hot body, the equipment is not particularly well-suited to making miscellaneous or periodic temperature measurements. If it is desired to check the temperature of some process over a period of a few days, however, the equipment may be installed in a semipermanent manner, calibrated, and left to produce its record.

Illumination and Exposure Meters.—Taking advantage of the fact that the dry disk self-generating cells require no batteries to deliver an appreciable current under illumination of artificial or natural light, portable foot-candle meters and photographic exposure meters have been developed. These devices are simply light-sensitive devices directly connected to a current meter calibrated in foot-candles or in a unit which can easily be converted into exposure for either still or moving pictures. Since as much as 5 ma. or more of current can be secured from such cells as Weston Photronic or Westinghouse Photox in direct sunlight, a fairly rugged sensitive microammeter (50 μa, for example) may be used with a shunt which can be removed when measuring low values of illumination.[1] An exposure meter of this general type is also made by Rhamstine.

Photo-electric Integraph.—A device[2] which "extends the range of practical solution of mathematical problems through its usefulness in the evaluation of integrals having a variable parameter within the integrand, such as those found in the Fourier transform, the superposition (Duhamel's) theorem and certain other integral equations" has been described by Gray. The device is useful in the study of transients, *e.g.*, the determination of the a.c. transient of a network due to an applied voltage of any form, determination of solution of problems involving variable parameters such as thermionic tubes, rectifiers,

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[1] See U. S. Patent 1,779,574, Samuel Wein on a direct-reading photometer. See GOODWIN, W. N., JR., *Trans. Illum. Society*, vol. 22, p. 828, December, 1932; LAMB, A. H., *Instruments*, October, 1932.

[2] GRAY, T. S., *J. Franklin Inst.*, No. 1, p. 212, July, 1931.

or rotating machines, analysis of river flow, weather behavior and other irregular phenomena.

The device operates by passing radiation from a line source of light, with uniform brightness along its length, through apertures whose shapes represent the functions to be multiplied and integrated. Light from this source is permitted to fall upon a cardboard mask in which is cut an aperture corresponding in shape to the area under any given function. If this function is to be multiplied by another, the light is then permitted to fall on the second cardboard mask in which is the aperture corresponding to the second function. These masks are placed
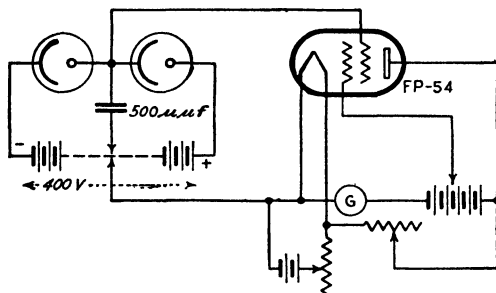
Fig. 78.—Electrical circuit of integraph.

some distance apart, and the light must pass through both of them before being integrated in an electrical circuit composed of the phototube and accessory apparatus. The amount of radiation which gets through to the phototube is a function of the product of these two functions, and the total amount of radiation which gets through is equal to the integral expressing the sum of the radiation getting through each infinitesimal portion.

The second mask may be reversed, or revolved with respect to the first, and so various complicated variable functions may be handled. Light from the source is permitted to fall on one phototube after passing through the cardboard masks, and by an optical system upon another phototube; a shutter is provided to keep constant the amount of light getting to the two cells; therefore the position or opening of this shutter is proportional to the value of the integral under investigation.

A complete description of the principle of this interesting and useful machine will be found in the reference together with some typical problems solved by its use.

Curve Plotter and Follow-up Mechanism.—At the Massachusetts Institute of Technology where the Gray Integraph was developed an interesting and useful modification of the general principle of the integraph has been made. This is a system for automatically plotting a curve of predetermined characteristic, or after a curve has been obtained of making a mechanism follow it. For example, when the curve moves under a slit in a phototube and maintains a condition of no illumination the machine is on the correct path. If it strays from this path to right or left, the mechanism can be made to return to the path of zero (or maximum) light by means of the phototube circuits.

Phototubes in the Chemical Industry.—Success of color- or light-sensitive devices in other industries has impelled considerable research toward applying these devices to the chemical industry, particularly in the hope that automatic control of processes could be obtained. Many such processes involve changes of color; others involve changes in capacity; and in many the addition of an indicator makes possible automatic control. In all of these cases, color- or light-sensitive equipment is indicated.

The advantages of automatic control of such processes are obvious. At present the time of an experienced and expensive chemist, or at least a skilled laborer working under the direction of a chemist, is required to sample liquors, make corrective measures, and wait until the measures take effect, and then make new tests, or new corrections. The condition of health and fatigue of the tester, the illumination (where colorimetric tests are made), and other variables come into this procedure. Therefore, if color-sensitive equipment can relieve the chemist for other less fatiguing or more profitable work, it will prove-in even if it accomplishes nothing more. Indications are, however, that such equipment will speed up the process, and lower the cost in other ways.

Examples where the addition of an indicator, whose color is affected by the hydrogen-ion concentration, are as follows:[1]

[1] ALFRIEND, J. V., JR., *Am. Inst. Elec. Eng.*, Winter Convention, Jan. 23–27, 1933, New York City. Also *Chem. Markets*, vol. 32, pp. 233–236, March, 1933. See WALTERS, J. A., *J. Soc. Chem. Ind.*, vol. 54, pp. 258–261, Mar. 22, 1935. Different types of photo-electric cell are described, and their characteristics discussed. Photo-electric methods do not always pro-

In metal flotation the range of hydrogen ion concentration, over which the maximum recovery is possible, is very small. An indicator added to the filtered sample will have a definite shade according to the concentration. This may be done automatically as is the filtration. The color of this sample may be used to control the feed of lime for a definite hydrogen ion concentration either at the launder or in the flotation tanks.

In electrolytic reduction colorimetric methods may be used to determine the hydrogen ion concentration and thereby control the speed of pumps and electrolytic current to maintain control over the acid concentration of fresh electrolyte from the leaching vats and the spent electrolyte from the tanks together with the flow of make-up acid if required. By the same process the acidity of waste liquors may be indicated and regulated.

In electrolytic refining where the best power efficiency is obtained at a definite hydrogen ion concentration colorimetric methods are again indicated. Since the concentration decreases as the electrolyte increases in copper content, proper control is desirable. The speed of circulation pumps and the flow of current in the stripping tanks may be controlled by photo-electric apparatus in accordance with the hydrogen ion concentration.

Municipal water plants frequently use chlorine for purification, and it is necessary to control the amount of excess chlorine. An indicator added to samples may be passed in front of color-sensitive equipment and thereby give an indication of the residual chlorine. The apparatus can be adapted to control the flow of liquid chlorine to the water.

In paper mills the acidity of the paper stock solution and the concentration of black liquor must be regulated within close limits. An indicator will give the required variable for photo-electric apparatus to control the concentration; the opacity of the black liquor is a function of its concentration.

There are other cases where a complete analysis of the color of a substance, for example, an oil or fat, is necessary or desirable to give a clue to its chemical constitution or to indicate whether or not it has the same or different physical properties than another

vide the best solution to a problem, and simpler alternatives may be found. If used for measurement of changes in lighting or of color, compensation methods should be adopted as far as possible. See *Electronics*, December, 1935, for the applications of tubes to the oil industry.

similar substance. Such cases are described in the foregoing; they involve the use of color-analyzing equipment already discussed.

Two colorimetric regulator schemes have been described[1] for service in the control of chemical processes of the nature described in the foregoing. One is a balanced-bridge arrangement using two phototubes to inspect simultaneously the light transmitted through a sample of the liquor under test and the light transmitted through a standard sample. Recalibration is required from time to time to compensate changes in the circuit or ageing
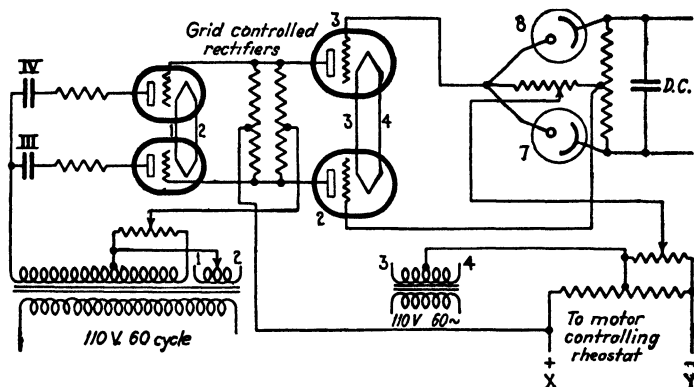
FIG. 79.—Balanced-bridge colorimetric regulator.

of the tubes. This arrangement, shown in Fig. 79, may be used as an indicator as well as a regulator.

If, for example, it is desired to control the speed of a conveyor which brings lime to a process for the purpose of controlling the hydrogen ion concentration, the circuit of Fig. 79 may be used. It will maintain the speed constant between corrective impulses received from the light-sensitive tubes. The actual speed-regulating circuits are not shown as they may be any of these several schemes described elsewhere in this book. The mechanical equipment is not shown; it will naturally differ for each installation. The equipment may be used to control the speed of motors, the opening or shutting of valves operated by solenoids or motors, or motor-operated rheostats, or other equipment encountered in the regulation of the flow of liquids, solids, or

[1] ALFRIEND, *loc. cit.*

The operation of the circuit is as follows: Two phototubes are supplied with direct current from a rectifier-filter system from alternating current.   A potentiometer constitutes one side of a bridge, and the two phototubes the other side.   The two phototubes are illuminated from the same light source.   In front of one phototube is placed a standard color sample in a glass tube, while the fluid to be controlled flows through a similar glass tube in front of the other phototube.   Variations in light intensity due to varying lamp voltage will not have any effect on such a balanced-bridge circuit.   If the alkalinity of the fluid changes, the bridge becomes unbalanced so that the voltage on the grid of an amplifier tube associated with this phototube will differ from the grid voltage on the amplifier of the other phototube. This unbalance is amplified and makes the grid of a grid-controlled rectifier tube more negative and the grid of another tube positive.   Positive grid bias on the rectifier tube causes a breakdown of the tube so that, for example, a relay will become energized, close its contacts, and affect the flow of liquid past the phototube systems.   The amplifier tubes are connected in a Wheatstone-bridge circuit which is normally balanced.   For this reason, variations in supply voltage will not affect the calibration of this part of the equipment.

Null Method of Colorimetric Control.[1]—A second method of utilizing the color-sensitive qualities of phototubes is a null method and is somewhat simpler than the method described, for the reason that it uses but a single photocell.   Recalibration is not necessary in this method since by the very definition of the method, no indication or control is made when the varying chemical is correct.   The null method cannot control and indicate at the same time.   Both the balanced bridge and the null method will operate either on color changes or by changes in opacity.

The phototube in the null method inspects the light from the sample and the standard simultaneously, by a system of mirrors and lenses through two different paths so that the light passes through the standard and also through the unknown liquid.

An apertured diaphragm is rotated in the path of the two beams so as to vary the cross section of the beams permitted to pass through the two liquids.   The sum of the apertured areas A and B are always equal to unity, the aperture A varying from

[1] **Alfriend**, *loc. cit.*

zero to 100 per cent, while the aperture B varies from 100 per cent to zero.

Thus, if the light-transmitting qualities of the two liquids are identical the illumination of the phototube will be unchanged as the diaphragm is rotated and therefore the output of the
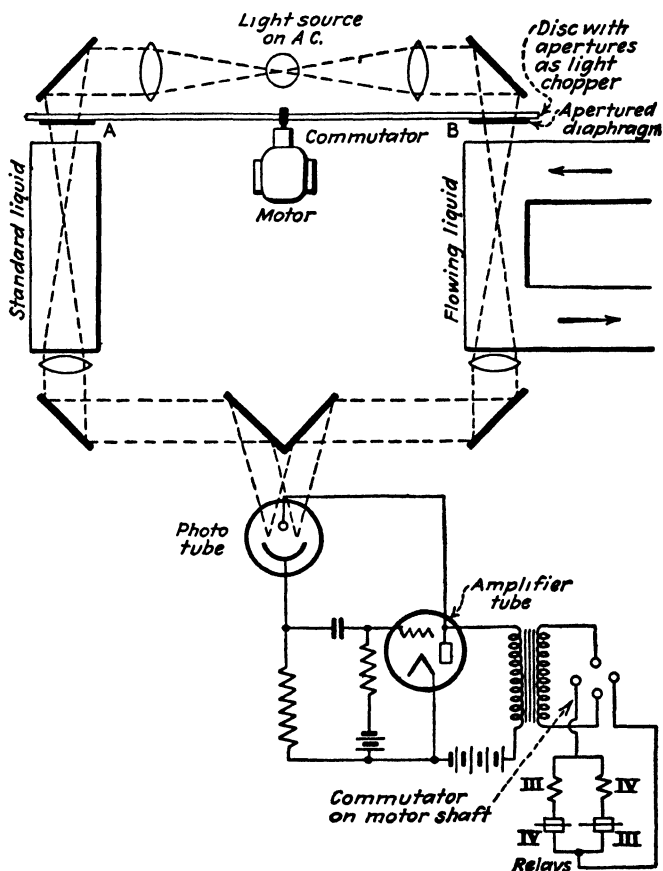
FIG. 80.—Null method of colorimetric control by phototube.

amplifier tube or its plate current will be constant direct current. With constant direct current impressed on the primary of a transformer in the output of the amplifier there will be no output from the secondary.

If the light-transmitting quality of one of the liquids deviates a small amount from that of the other, the illumination of the

phototube will vary as the diaphragm is rotated and the plate current of the amplifier will therefore become pulsating direct current. With pulsating direct current impressed on the primary of the transformer the secondary will deliver only the alternating component which in phase position and in magnitude will be proportional to the deviation in light-transmitting qualities of the unknown fluid from that of the standard fluid. This alternating component is rectified by a mechanically driven commutator on the shaft of the motor which drives the diaphragm. The direct current thereby obtained will be proportional in sign and magnitude to this same deviation in light-transmitting quality and will control a speed-adjusting rheostat and timing cycle to correct for the unbalanced condition.

Since this circuit is a zero or "null" method and this feature is obtained by filtering out the direct component of the plate current of the amplifier tube, the regulator is insensitive to steady variations in applied voltage as affecting the circuit or the light source, and it is not affected by steady variations in temperature or changes in sensitivity of the tube itself within its working range.

A considerable amount of work on the uses of various electron tubes in chemical process has been done by Partridge. A very extensive bibliography on this subject has been compiled by him and will be found in *Industrial and Engineering Chemistry*, vol. 2, page 207, July 15, 1930. Among other uses of photocells, Partridge mentions apparatus for the measurement and control of chlorine and hardness of water (the latter measurement being accurate to a quarter grain per gallon) hemoglobinometry, fluorescence measurements, micro-analysis, pH measurements, automatic titration, solubility products, organic analysis, and reaction control.

Measuring pH values with a simple circuit consisting of only a phototube connected in series with a battery across a grid resistance in the input to an amplifier has been successful. A milliammeter in the plate circuit records the changes in grid voltage as a function of pH values. Partridge found that titration could be controlled very nicely using simple circuits consisting only of a phototube and the accompanying amplifier in whose plate circuit was a relay arranged to shut off the addition of solution. Stirring the solution with a paddle up to rates of

600 r.p.m. was found not to affect the titration control provided the production of air bubbles did not interrupt the light rays from a source through the solution to the phototube. Proper filters were used, varying with the color of the indicator used.

According to Lee,[1] the photocell plus amplifier and milliammeter exceed visual precision in measuring acidity or alkalinity by about ten times, and more in regions of the spectrum where the eye is less sensitive.

Opacity-measuring Equipment.—Numerous uses of light-sensitive tubes in measuring opacity of solutions or of paper stock, etc., have been made. Several types of this apparatus are on the market for sale, and in other cases engineers have applied a phototube to their own problems.

"Sedimentation methods employed for analysis of soils have called for a simple and rapid method of measuring the colloid content of a suspension, and attempts are being made to overcome this with the optical opacity of the suspension."[2]

The principle involved is that of a flicker photometer in which the flicker is detected by a photocell followed by an amplifier and loud-speaker. Two beams of light from a common source are directed over two paths to the phototube. If the two beams have equal intensity, they are interrupted alternately, and thus if the two beams are of equal intensity, they produce uniform illumination and note from the loud-speaker, and a steady current from the phototube. The material to be tested is placed in one beam, and if it changes the illumination arriving from this beam an alternating current is produced by the phototube which is amplified to become audible.

To measure the opacity, another beam of light from the same source is reflected to the cathode and passes through a sectored disk in such a manner that the light from this third beam passes to the phototube. At the same instant the light from the substance to be measured arrives there. The third beam may be controlled in intensity by a shutter. Thus the loss of light caused by the more or less opaque material may be made up by this third beam and the intensity required to balance out the loud-speaker note is a measure of the light lost in the substance.

[1] LEE, JAMES A., *Trans. Electrochem. Soc.*, vol. 59, 1931.
[2] WILSON, J. S., A Sonic Nephelometer, *J. Sci. Instruments*, April, 1933.

After the system is balanced, the liquid to be measured is placed in one of two parallel-sided glass boxes and the shutter on the third beam of light adjusted until the note again disappears from the loud-speaker. Then the boxes are removed and an Ilford wedge screen is placed in the third beam of light until the note disappears again. The opacity of the material can then be read directly from a calibration of the wedge.

The null method removes any necessity for a photocell having definite and known response to light of a given intensity. A caesium gas-filled cell is used. The apparatus is sensitive to one scale division on the wedge corresponding to about 1 per cent absorption.

Bausch and Lomb Opacimeter.—This is an instrument for measuring the opacity of paper, a characteristic of paper of vital interest to both manufacturer and user. Opacity is the property which prevents printing on the page behind from showing through. It is expressed in terms of two qualities, "contrast ratio" and "printing opacity." Both these quantities, are ratios; they differ in the method by which they are measured. In measuring contrast ratio the paper is backed by a block of magnesium carbonate and then by a block of black. In measuring the printing opacity the paper is backed by a number of sheets of the paper, the number being such that adding further sheets will not alter the reading. Then the paper is backed by the black body.

Light is reflected from the paper in the two measurements. Thus when measuring contrast ratio, the value of current when the paper is backed by black body divided by the current when the paper is backed by magnesium carbonate is the desired value. In a similar manner the second ratio is secured. The circuit is simple. A 32-cp. 6-volt lamp is run slightly over 6 volts to increase the intensity and whiteness of the illumination. A voltage regulator on the transformer of the a.c. model maintains the temperature of the lamp more or less independent of the line-voltage variations. A variable diaphragm gives control over the amount of light falling on the sample. Over a certain range the instrument is direct reading.

Photo-electric Colorimeter.—In measuring the color of a solution in chemical analysis, photo-electric apparatus has proved its value. For example,[1] visual estimation of the color of yellow

[1] SELWYN, E. W. H., *J. Sci. Instruments*, April, 1933.

sols obtained in the analysis of dilute silver solutions was found to be difficult. A phototube with proper filters, etc., simplified the process and made it more accurate. The circuit shown in Fig. 81 and a potassium photocell were used.

The procedure was as follows: The bridge composing the amplifier and phototube was adjusted so that some convenient reading was obtained on the microammeter (250 μa full scale). Then the solution was moved into the path of the light beam. This caused a deflection of the microammeter which was returned to its original position by means of a uniformly graded wedge. The reading of the scale on the wedge was a measure of the strength of the solution. The rack and pinion movement of
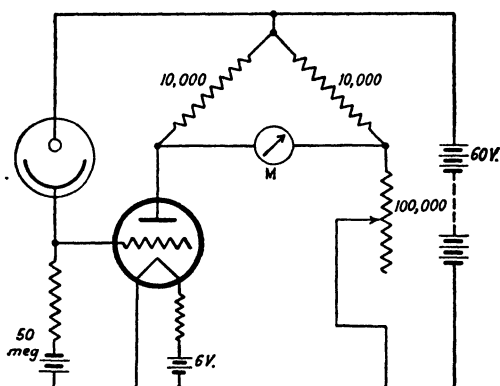
FIG. 81.—Circuit that will measure concentration of a solution (by color).

the wedge enabled its position to be known to an accuracy of 0.2 mm. or 0.002 in density. Thus the 1,000th part of the maximum concentration of a given solution could be determined. In the particular use (silver sols) a maximum concentration of 15 mg. of silver per liter was measurable. Then at any concentration below this figure the accuracy of measurement was about 0.015 mg. per liter.

Photo-electric Photelometer.—An interesting application of light-sensitive cells is an instrument developed by the Central Scientific Company after the work of Drs. Sheard and Sanford of the Mayo Clinic and Mayo Foundation, to determine rapidly the grams of hemoglobin per cubic centimeter in blood samples.

The photo-electric Photelometer is an instrument for analyzing samples containing the same ingredient. It is based on the laws

of light transmission of substances formulated by Lambert and Beer. According to this law, when the light rays from a constant source of illumination are passed through a solution of a substance and a light filter with transmission characteristics corresponding closely to the absorption characteristics of the solution, the intensity of the transmitted beam of light is proportional to the
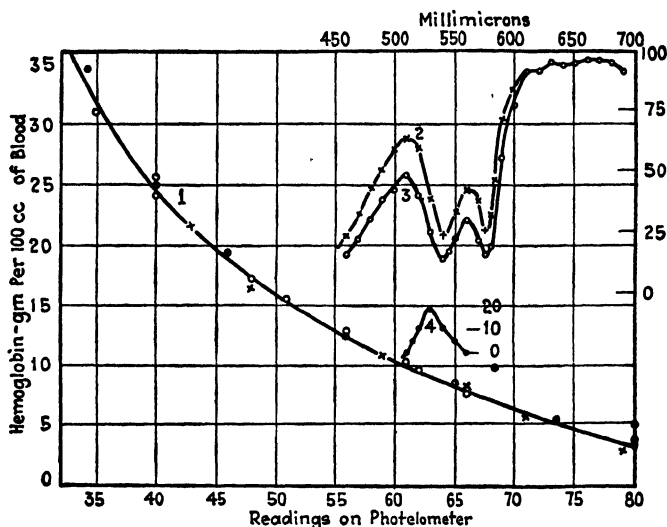
Fig. 82.—Curve 1. Relationship between readings on the Photelometer and grams of hemoglobin per 100 cc. of blood as determined by Van Slyke method. Curves 2 and 3. Spectrophotometric transmission curves of blood showing absorption bands with minimal transmissions at approximately 585 and 540 millimicrons respectively. Curve 4. Spectrophotometric transmission of spectral filter used in the quantitative estimation of hemoglobin. This filter transmits spectral energy only in the region corresponding to the 540-millimicron band of hemoglobin.

concentration of the substance in solution. Mathematically, the concentration is proportional to the negative logarithm of the transmitted light intensity. The logarithmic function does not complicate the calibration of the instrument, as semi-logarithmic coordinate paper is used to plot the relation of scale readings to known concentrations of the substance sought. By this method only a few calibration points need be determined and the approximately straight line joining them will form the calibration curve. When the Photelometer is once calibrated for a substance, the unknown sample is placed in the glass cell.

inserted in the light path and the scale reading taken from the microammeter that indicates the intensity of the light transmitted. The concentration in grams per 100 cc is obtained through reference to the calibration chart.

The essentials of the instrument are: a steady source of illumination, a diaphragm for adjustment of the light intensity to bring the meter reading to the same initial reading, a glass

FIG. 83 —Trans-o-meter (*Westinghouse*) for measuring transmittancy.

absorption cell to hold the unknown solution, a light filter to transmit only the light rays in the absorption band of the substance, and a light-intensity measuring device.

In the Photelometer, a Weston Photronic cell and microammeter for indicating the value of the current generated, make up the light-intensity measuring device.

To eliminate difficulties due to line-voltage variations, affecting the intensity and spectral characteristic of the illumination, a special transformer supplies 6.5 amp. at 6.1 volts to the lamp and maintains the illumination constant to within 1 to 2 per cent.

Trans-O-Meter (Westinghouse).—This is a simple portable instrument indicating on one instrument and without calculations the transmittancy of flat materials. This term is applied to the ratio of the light transmitted through to the upper surface,

to the amount of light that strikes the lower surface of any object. Any flat object less than ⅜ in. thick can be tested with this instrument; for example, samples of paper, fabrics, cellophane, glassine paper, or two or more similar materials such as cloth, provided exactly the same portions of a design are placed over the aperture. The instrument is designed only for measuring plain colors and for materials having a homogeneous surface and texture.

A Photox (dry disk of the copper oxide type) light-sensitive unit is employed with a sensitive microammeter.

Transparency Meter (Weston).—An instrument for measuring the transparency of paper and other materials, using the photronic cell, has been developed by Weston. The apparatus is composed of a Mazda lamp (of a wattage suitable for the measurement to be undertaken), a time switch to limit the burning time of the lamp and thus to reduce the effect of ageing, a light-sensitive cell, and external microammeter (50 microamp., full scale), and proper mechanical arrangements for interposing the liquid or other material to be tested.

Trichromatic tests of liquids may be made by the use of the proper filters for which provision is made in the instrument.

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See also bibliography at end of preceding chapter.

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GULLIKSEN and VEDDER, "Industrial Electronics," John Wiley & Sons, Inc., 1935.

Register Control.—One of the most useful applications of phototubes and accessory amplifiers and grid-controlled rectifiers is in the maintenance of synchronism between two movements, *e.g.*, the running of a web of paper or cloth through a press and a cutting device which cuts this web into sections each of which contains a complete design as printed by the press. By hand this is done by occasional adjustments of the machine so that the knife does not cut through some portion of the pattern.

Westinghouse engineers have been very active and successful in attacking problems of this nature and have applied the various methods to many forms of register applications. Good descriptions of several of the methods used will be found in Gulliksen and Vedder, "Industrial Electronics." Other references will be found in the bibliography on page 459.

Problems and solutions of this type resolve themselves into several types. In one, the paper is fed continuously; in another, there is an intermittent feed. The latter is found in slow-speed machines and is more likely to get out of step than is the continuous-feed type. If the paper moves faster than perhaps 100 ft. per minute, the continuous method is used. The paper may always be fed at a rate faster than desired. Then when the design gets too far out, the corrective measures will be applied. In another type the corrective mechanism can operate backward or forward, speeding up the paper or retarding it. Bag machines operating at 500 ft. per minute are controlled by this method.

The principle, so far as electronics is concerned, is simple. A spot of color is placed on the roll of paper. This spot is scanned by a phototube. If it is in the proper position with respect to the cutting knife, nothing happens. But if it is not in this position, the correction is applied. In one method a two-circuit timing switch is driven from the operating shaft of the cutter knife to provide a means of determining whether the spot passes ahead of or behind its proper point in the machine cycle. The impulse set up by the spot of color passing by the phototube is fed to the timing-switch circuit.

As shown in Fig. 84, if both circuits are open when the spot passes, the cutters operate, but if the spot is behind or ahead of its proper position, the corrective measures are applied.
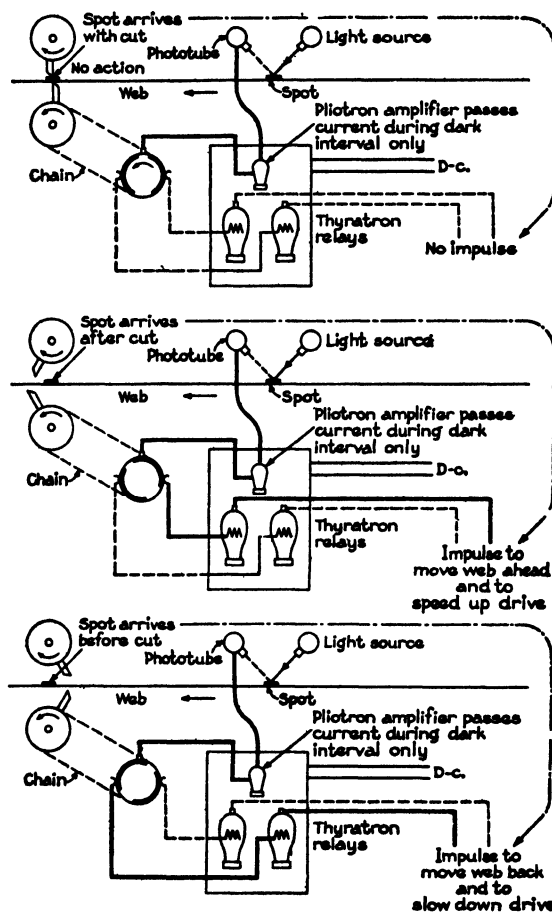
FIG. 84.—Register-control set-up showing actions in determining necessity for, and direction of, corrections to be made.

These consist of grid-controlled rectifiers acting as contactors and operating with direct current on the anodes. It takes but a very small fraction of a second to cause these tubes to go into action, and they remain conducting until a time relay opens the d.c. circuit or until a switch connected to some portion of the

mechanism opens the circuit. Then they are reset for another correction.

In a typical installation (General Electric) a 57-type tube acts as a phototube amplifier; a 56 is used as the timing tube; an 83 rectifier supplies power; and the phototube and controlled rectifiers are the only tubes that cannot be obtained at any radio service shop.

Experience has shown that wastage can be cut in half by phototube control compared to manual control. The spot of color may affect the phototube by transmission of light or by reflection. In the latter case additional amplification is usually required. Watermarks in paper have been utilized as the control.

The spot need be no more than $\frac{1}{32}$ in. in size in the direction of motion of the paper but should be from $\frac{1}{4}$ in. to $\frac{1}{2}$ in. in length, perpendicular to the motion of the paper, so that lateral movement will not throw it out from under the scanned track.

In uncontrolled equipment, out-of-register occurs very quickly. Thus, if an error of only one-tenth of 1 per cent should occur with a wrapper 1 ft. in length, the position of the cut would creep approximately $\frac{1}{8}$ in. for each 10 units passed through the machine. Or, again, if a machine cuts two hundred 36-in. sheets per minute, a unit error in the ratio of 1 to 7,200, or 0.005 in., will accumulate at the rate of 1 in. per minute. In this case spoilage begins in 15 sec. Experience has indicated that stretch or shrinkage of a web of material with varying moisture conditions and varying tensions may easily cause errors of this magnitude. It should be noted that such an error in the length of one individual sheet is usually not important—it is because the errors are cumulative that they are especially important when handling a printed web.

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Elevator-floor Leveling.—Westinghouse applies phototubes to the leveling of elevators by using two tubes with a common source of light. As the car approaches its proper floor, the leveling circuit is set up, and the speed of the car is reduced. One phototube is cut off, but the other continues to pass current. At the exact floor level, both tubes are cut off, and the elevator motor is shut down. If the car overshoots, the phototube that has been dark in the preceding operation becomes illuminated, and the elevator motor is reversed. Most of the elevators in Rockefeller Center, New York City, are controlled by this system.

Another use of phototubes on elevators is to prevent the closing of the doors if either of two beams of light across the door is eclipsed by a person entering or getting out or by a bundle carried by a passenger.

Miscellaneous Phototube Applications.—Counting by size, automatic batching, or weighing, routing of parcels depending upon their dimensions or marks placed upon them are rather obvious but very important uses of light beams and phototubes.

Tension of wire in reeling may be controlled by letting a beam of light be eclipsed by a weight carried on the wire. The speed of paper or other material through a process may be controlled by letting a loop of it eclipse a beam of light.

Technical and trade literature is replete with references to applications of these general principles.

CHAPTER VII

RECTIFIERS, CATHODE-RAY TUBES, MISCELLANEOUS TUBES, AND CIRCUITS

TWO-ELEMENT RECTIFIERS

Vacuum and Gaseous Rectifiers.—Little need be said about these types of thermionic tubes. The literature on the subject is profuse, with respect not only to the tubes themselves but to their application. They are the earliest forms of electron tube. A cathode supplies electrons which are attracted toward the anode when the latter is positive with respect to the former. The cathode may be a filament, a heater type of cathode, or pool of mercury, or even a cold cathode. Their application is that of rectifying alternating current so that direct current may be obtained from an a.c. source. Tubes of all sizes and power capabilities exist.

The gas employed (0.005 to 0.05 mm. Hg) in two-element rectifiers in common use may be argon, neon, or helium. Usually, however, the partial atmosphere is supplied by mercury vapor secured from a drop or so of mercury in the envelope which vaporizes when the cathode heats up. As already explained in such gaseous tubes the space charge, which is the factor limiting the amount of current in a vacuum tube, is neutralized by the positive ions produced in collisions between electrons and mercury atoms. This results in a low-voltage drop—about 15 volts for mercury—which is practically independent of the current taken from the tube.

Gaseous tubes can carry much higher currents than vacuum tubes; the absence of space charge with its resultant voltage drop and power dissipation permits larger electrode spacing within the tube and the use of smaller electrodes for a given current. The vapor pressure is sufficiently low so that when the anode is negative and the cathode positive, little or no current flows in the inverse direction, even though the voltage across the tube may be several thousand volts.

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FIGURE	LOAD CURRENT WAVE FORM	TUBE CURRENT WAVE FORM
1a-Single Phase - ½ Wave	100 E_T Max — 1 cycle	Conducting Time ½ Cycle — 1 cycle
1b-Single Phase - Full Wave	100 E_T Max — 1 cycle	Conducting Time ½ Cycle — 1 cycle
1c-Single Phase - Full Wave	100 E_T Max — 1 cycle	Conducting Time ½ Cycle — 1 cycle
1d Three Phase - ½ Wave	100 E_T Max — 1 cycle	Conducting Time ⅓ Cycle — 1 cycle
1e-Three Phase - ½ Wave Double Y same as straight 6 Phase	100 E_T Max — 1 cycle	Conducting Time ⅙ Cycle — 1 cycle
1f-Three Phase - ½ Wave Double Y with interphase transf 6 Phase wave form - essentially 2 and 3 Phase systems in parallel	10.866 E_T Max — 1 cycle	Conducting Time ⅓ Cycle — 1 cycle
1g-Three Phase - Full Wave Gives same wave form as 6 Phase	173 E_T Max — 1 cycle	Conducting Time ⅓ Cycle — 1 cycle

Note - $A = E_T \max \sin\theta\, d\theta$
$A^2 = E_T^2 \max \sin^2\theta\, d\theta$

Fig. 1.—Typical rectifier

LOAD VALUES			TUBE VALUES			INVERSE PEAK VOLTAGE	USEFUL CURRENT RATIOS			
Peak	Edc Average	RMS	Peak	Average	RMS		Tube Av / Load Av	Tube RMS / Load RMS	Tube RMS / Tube Av	Load RMS / Load Av
100 Et Max	0.318 Et Max, 0.448 Et RMS, $\frac{1}{2}\pi/\frac{\pi}{6}$ A	0.500 Et Max, 0.705 Et RMS, $\sqrt{\frac{1}{2}\pi/\frac{\pi}{6}}$ A	100 Et Max	0.318 Et Max, 0.448 Et RMS, $\frac{1}{2}\pi/\frac{\pi}{6}$ A	0.500 Et Max, 0.705 Et RMS, $\sqrt{\frac{1}{2}\pi/\frac{\pi}{6}}$ A	100 Et Max	3.14 Edc	100	100	1.57	1.57
0.5 Et Max	0.318 Et Max, 0.448 Et RMS, $\frac{1}{2}\pi/\frac{\pi}{6}$ A	0.355 Et Max, 0.5 Et RMS, $\sqrt{\frac{1}{2}\pi/\frac{\pi}{6}}$ A	0.5 Et Max	0.159 Et Max, 0.224 Et RMS, $\frac{1}{2}\pi/\frac{\pi}{6}$ A	0.250 Et Max, 0.357 Et RMS, $\sqrt{\frac{1}{2}\pi/\frac{\pi}{6}}$ A	100 Et Max	3.14 Edc	0.500	0.705	1.57	1.11
100 Et Max	0.636 Et Max, 0.896 Et RMS, $\frac{1}{2}\pi/\frac{\pi}{6}$ A	0.710 Et Max, 100 Et RMS, $\sqrt{\frac{1}{2}\pi/\frac{\pi}{6}}$ A	100 Et Max	0.318 Et Max, 0.448 Et RMS, $\frac{1}{2}\pi/\frac{\pi}{6}$ A	0.500 Et Max, 0.706 Et RMS, $\sqrt{\frac{1}{2}\pi/\frac{\pi}{6}}$ A	100 Et Max	1.57 Edc	0.500	0.705	1.57	1.11
100 Et Max	0.825 Et Max, 1.161 Et RMS, $\frac{1}{2}\pi/\frac{5\pi}{6}$ A	0.835 Et Max, 1.175 Et RMS, $\sqrt{\frac{1}{2}\pi/\frac{5\pi}{6}}$ A²	100 Et Max	0.275 Et Max, 0.388 Et RMS, $\frac{1}{2}\pi/\frac{5\pi}{6}$ A	0.483 Et Max, 0.684 Et RMS, $\sqrt{\frac{1}{2}\pi/\frac{5\pi}{6}}$ A²	1.731 Et Max	2.095 Edc	0.333	0.579	1.76	1.01
100 Et Max	0.955 Et Max, 1.345 Et RMS, $\frac{6\pi}{2\pi}/\frac{2\pi}{3}$ A	0.978 Et Max, 1.380 Et RMS, $\sqrt{\frac{2\pi}{2\pi}/\frac{2\pi}{3}}$ A²	100 Et Max	0.159 Et Max, 0.224 Et RMS, $\frac{1}{2}\pi/\frac{2\pi}{3}$ A	0.389 Et Max, 0.550 Et RMS, $\sqrt{\frac{1}{2}\pi/\frac{2\pi}{3}}$ A²	200 Et Max	2.095 Edc	0.167	0.397	2.45	1.02
0.866 Et Max	0.828 Et Max, 1.168 Et RMS, $\frac{6\pi}{2\pi}/\frac{2\pi}{3}$ 0.866 A	0.847 Et Max, 1.175 Et RMS, $\sqrt{\frac{2\pi}{2\pi}/\frac{2\pi}{3}}$ 0.866 A²	0.433 Et Max	0.138 Et Max, 0.196 Et RMS, $\frac{6\pi}{2\pi}/\frac{2\pi}{3}$ 0.433 A	0.237 Et Max, 0.334 Et RMS, $\sqrt{\frac{2\pi}{2\pi}/\frac{2\pi}{3}}$ 0.433 A²	1.73 Et Max	2.09 Edc	0.167	0.280	1.72	1.02
1.73 Et Max	1.65 Et Max, 2.33 Et RMS, $\frac{6\pi}{2\pi}/\frac{2\pi}{3}$ √3 A	1.69 Et Max, 2.39 Et RMS, $\sqrt{\frac{2\pi}{2\pi}/\frac{2\pi}{3}}$ 3 A²	1.73 Et Max	0.552 Et Max, 0.778 Et RMS, $\frac{2\pi}{2\pi}/\frac{2\pi}{3}$ √3 A	0.948 Et Max, 1.328 Et RMS, $\sqrt{\frac{2\pi}{2\pi}/\frac{2\pi}{3}}$ 3 A²	1.73 Et Max	1.05 Edc	0.333	0.561	1.72	1.02

* Divide by entire circuit resistance to get amperes

circuits and output.

The definitions relating to gaseous rectifiers are given under controlled rectifiers. The chief use for these tubes is to supply high-voltage direct current from low-voltage alternating current. Thus for radio transmitters where high d.c. voltages are desired at fairly low currents these tubes have provided the power for years. Where still greater currents are required, pool-type tubes are used, often metal-clad instead of enclosed in glass, and with pumps constantly attached to keep the vacuum at the required value. Often these tubes are equipped with control electrodes for better regulation or control—then they become grid-controlled rectifiers of the type described in Chap. IV.

Current Required and Choice of Circuit.—There is a distinct connection between these two factors. In general, circuits of low-power requirements are single phase; when greater power is required three-phase circuits are advantageous. Higher phase supply is advantageous in that less filtering is required to get direct current from the a.c. source. The following table taken from the General Electric data on Phanotrons (gaseous rectifiers) shows the relation between the circuit requirements when used with a tube of 12.5-amp. average current rating.

	Amperes
Single-phase—one tube (limited to reasonably non-inductive loads)	12 5
Single-phase, two tubes	25 0
Three-phase, three tubes.	37 5
Scott connection, four tubes .	50 0
Three- or six-phase, six tubes . .	75 0
Twelve-phase, twelve tubes	150 0

Typical Rectifier Circuits.—The table on page 462 taken from the Westinghouse Tube Handbook gives a good idea of the various types of rectifier circuits, their current values, wave form of the rectifier current, etc.

Types of Rectifier and Filter Circuits.—There are two general types of circuit depending upon whether one or both halves of the a.c. cycle are rectified.

After the alternating current is rectified, it is sent through a filter consisting of shunt capacity and series inductance to smooth out the impulses and provide as pure direct current as is desired. For communication purposes this direct current must be free from ripple to a varying extent depending upon conditions.

Thus a microphone amplifier, which is followed by a very considerable amplification before the final result is put into a loudspeaker, must be powered from a source of very pure direct current, or the resultant amplified ripple voltage would be intolerable.

The filter has two general forms, with either a capacity or an inductive input. A capacity input places a capacity directly across the output of the rectifier and the input to the filter. The inductance input has a small inductance between the rectifier and the input to the filter. These are shown in Fig. 2. The latter puts much less load on the rectifier but is less economical in that the output voltage is somewhat lower. A capacity input may have very high peak currents into it which must be
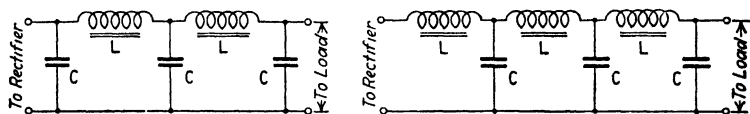
Fig. 2.—Capacity and inductive input filters.

supplied by the emission of the rectifier tube. The inductance filter has peak currents much lower in amplitude and the life of the tube is correspondingly greater.

These filters and rectifier circuits are described in considerable detail in the literature; the handbooks for electrical engineers or the "Radio Engineering Handbook" (McGraw-Hill Book Company, Inc.) have good discussions. The bibliography below on the subject of rectifiers and filters will provide the engineer with considerable information.

High-vacuum Rectifiers.—Because of the high insulation in the high-vacuum rectifiers they are adapted to circuits in which very high voltages are found. Thus two-element high-vacuum rectifiers are available which will pass 1 amp. at 150,000 volts. These tubes are used for cable testing, supplying x-ray equipment with the proper high voltages and other places where a high voltage, low d.c. current is desired.

A typical single-wave tube is the 281. Full-wave rectifiers of the 80 type are widely used in radio receiving sets to supply power to the amplifier tubes.

The voltage drop in such tubes is very high compared to the drop in gaseous rectifiers. Their regulation, therefore, is

inherently poorer than with gas tubes. They seem to be some-what easier to filter, however. By the use of close spacing between cathode and anode it is possible to reduce the voltage drop to approach that of a gas tube.

Applications of Rectifiers.—Aside from the natural and obvious production of direct current from alternating current there are various uses for rectifiers. The vacuum-tube voltmeter (Chap. III) is a rectifier in that there is a production of some direct current when an a.c. input is applied to the tube. This rectification is produced by overbiasing the grid of the tube so
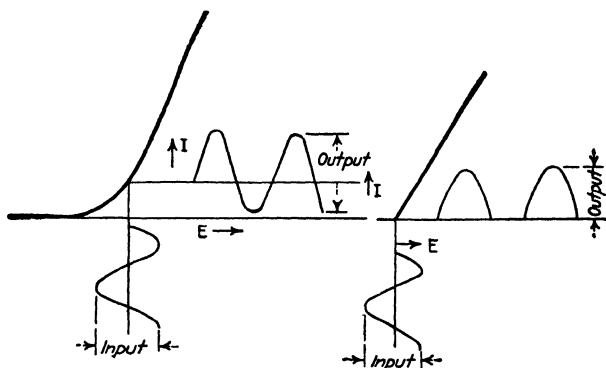
Fig. 3.—Rectification at nonlinear portion of characteristic—perfect rectification at right.

that distortion takes place, the output current waves not being identical in form with the input voltage waves. The more efficient the rectifier the more direct current is produced from a given a.c. input voltage.

In many communication circuits, or even industrial circuits, the rectifier tube may actually be a three-element tube with two of the three elements connected together, for example, grid and plate, or grid and cathode, rectification taking place between the remaining electrode and the two others connected as a single element. Rectification requires a nonlinear characteristic which may be a continuous curve or a straight line intersecting an axis at a sharp angle, as in Fig. 3. If this type of rectifier is utilized, it operates most efficiently when the operating point is at the point where the curve intersects the axis.[1]

[1] On the use of a full-wave rectifier in theater-lighting control, see ROLLINS, DANIEL M., and B. S. BURKE, Theater Lighting Control, *Elec. J.*, November, 1935, p. 477.

Rectifier for Power Systems.—The first thermionic rectifier equipment used to feed power into a 250-volt d.c. system of a large public utility was installed in the Salem Street substation of the Edison Electric Illuminating Company of Boston. It is an excellent example of the efficient conversion of alternating current to direct current, using hot-cathode rectifiers of considerable current output in which high-voltage alternating current is supplied to the rectifiers and low-voltage direct current secured from them.

Ordinarily a large number of low-voltage cables radiate from a substation containing large rotary converters or motor generators. By the use of rectifiers the expense of such low-voltage feeders and their losses may be saved.

In the Boston installation the equipment was designed for 600-amp. direct current. The apparatus consisted of a main power transformer with a tapped primary, an interphase transformer, an a.c. contactor, a high-speed d.c. circuit breaker, an auxiliary power-supply transformer, two current transformers in the incoming high-voltage leads, and a surge eliminator for the protection of the transformer.

The primary of the transformer has six 1-per cent taps; the a.c. reactor is housed in the same tank with the transformer and connected in series with the transformer primary. This reactor has five steps, each of which will change the regulation at full load by 1 per cent. By using different combinations of taps various regulation curves can be obtained. The surge eliminator consisting of capacity and resistance is connected across one secondary winding of each leg of the transformer and across the interphase transformer. Its purpose is to damp out transients caused by unusual circuit conditions in the tubes or external to the circuit. The rectifier tubes in this equipment consist of a copper body which is the anode within which is the cathode and, of course, insulated from the anode. Provisions are made to maintain the temperature at desired values, the mercury pressure being maintained at a desired level by trapping some of the mercury and heating it by thermostatic control. The high-speed d.c. circuit breaker interrupts the current flowing in the d.c. system into the rectifier due to a fault in the latter. Proper provision is made to permit sufficient time to elapse between lighting the filaments and connecting the anodes to their source of voltage.

If an overload occurs, both a.c. and d.c. circuits are opened. The a.c. circuit closes again after a brief delay and the d.c. breaker closes after the cause of the overload has been removed. If the faulty condition remains, the cycle is repeated, and if
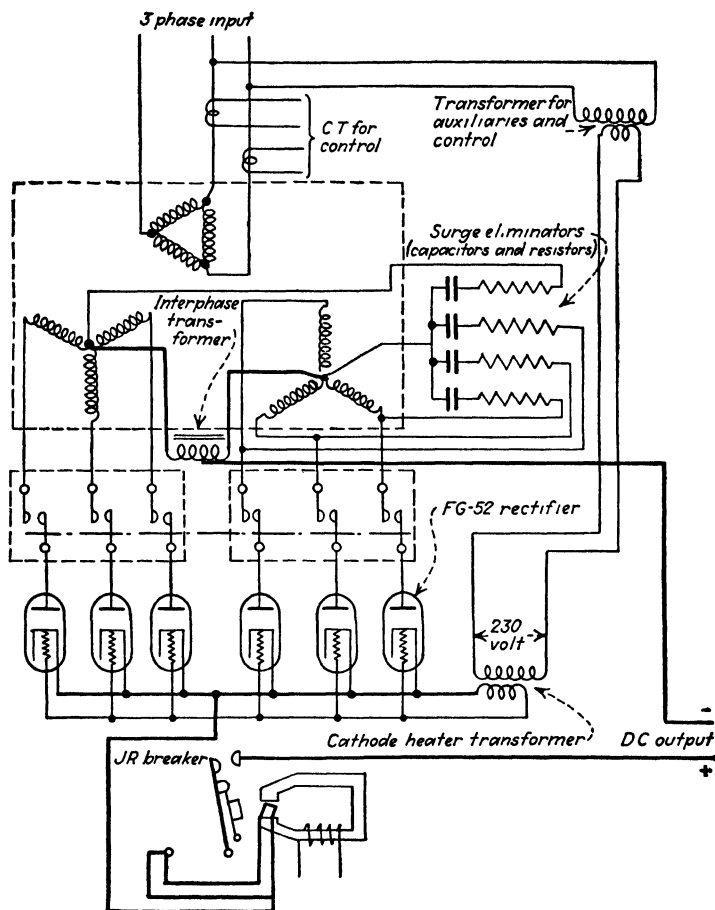
FIG. 4.—Circuit of rectifier supplying 250-volt d.c. system.

after three cycles of opening and closing the circuits, the condition continues, manual closing of the circuits is necessitated.

Rectifier Supplying Constant Voltages.—Good regulation may be obtained by using triode amplifiers in place of half-wave rectifiers by having changes in the a.c. line voltage automatically

change the grid bias of the rectifiers.[1] If one of the variables E_a (a.c. line voltage), E_d (d.c. voltage output of rectifier-filter system), E_g (bias on rectifier grids) is held constant, there exists a linear relation between the remaining two.   Table I gives data on several types of tube with different amplification factors. For a fixed line voltage the change in d c. output per volt change in bias is proportional to the mu factor of the tube.   Column 4 shows the change in grid voltage required to maintain the output voltage constant when there is a 1-volt change in line voltage. Columns 5 and 6 give an idea of the voltage output obtainable from several tubes and the voltage drop which will occur with a change in load resistance of R across filter output.

TABLE I

1	2	3	4	5	6
Type of tube	Mu factor	$\dfrac{\partial E_d}{\partial E_g}$ E_a const	$\dfrac{\partial E_g}{\partial E_a}$ E_d const	E_d for $E_p = 540$ r m s $E_g = -10$ $R = 60,000$	E_d for $E_p = 540$ r m s. $E_g = -10$ $R = 4,600$
210	8 0	6 25	0 82	482	190
2A3	4 2	3 80	1 65	612	340
250	3 8	3 37	1 67	585	270
245	3 5	3 33	1 60	595	310
281				655	370

A constant-voltage supply circuit using d c control on the grid is shown in Fig. 5.   This circuit has an undesirable operation characteristic in that a sudden change in line voltage of 1 volt or more produces a small transient in the output voltage.   This is due to the time lag introduced by C_4 and C_5 which causes the correcting voltage to reach the grids in a short time after it reaches the rectifiers.   This transient may last only a fraction of a second and is of the order of 0.5 volt.   A combination of alternating and direct current on the grids shown in Fig. 6 will get around this trouble.   The d.c. component of the grid bias is supplied from potentiometer R_2 across four 874 glow tubes.   The a.c. component, obtained from the resistor across the grid trans-

[1] RICHARDS, L. A , The Use of Triode Rectifiers to Supply Constant Voltages, *Rev. Sci. Instruments*, September, 1933, p. 481.

former, is 180 deg. out of phase with the plate voltage. If $V_2 = 10$ to 20 per cent of V_3, the regulation curves are fairly flat. Table II shows the regulation obtainable from this circuit.

TABLE II.—ALTERNATING-CURRENT GRID CONTROL;
210-TYPE TUBES; $\frac{1}{10}$ MA.

E_a	E_d
112.5	521.0
116.3	523.0
119.0	523.2
125 0	523.5
129.5	523 5
136.0	525.0
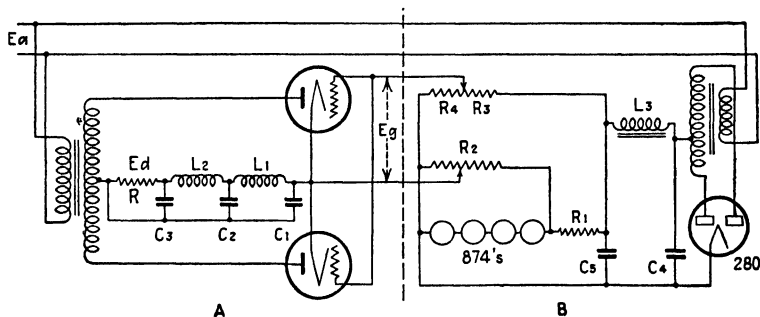
FIG. 5.—Rectifier with constant-voltage output.

$R_1 =$ 6,000 variable	$C_1 = 2\mu F$	$C_1 = 4\mu F$
$R_2 = R_3 = 100,000$	$C_2 = C_3 = 4\mu F$	$L_1 + L_2 = 30h$
$R_4 = 50,000$	$C_4 = 1\mu F$	$L_3 = 20h$
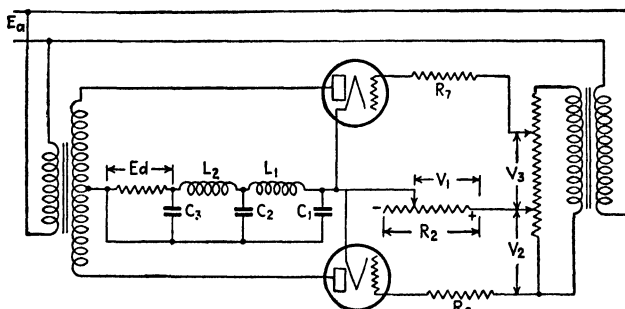
FIG. 6.—Modification of Fig. 5 to produce more stable output.

The circuit shown in Fig. 7 is taken from Street and Johnson[1] who state that a variation of 60 volts (1,580 to 1,640) changed the output voltage less than 1 volt. The circuit is limited to very small currents.

[1] *Jour. Franklin Inst.*, August, 1932.

Another voltage-stabilizing circuit[1] is shown in Fig. 8.   Used with a gaseous rectifier, filter, and triode stabilizer Kohler found
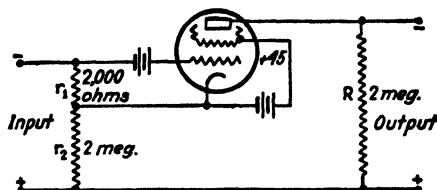
FIG. 7.—Circuit giving steady output with varying input.

that the voltage output varied from 149.5 to 149.7 over an input range of from 90 to 103 volts, while the unstabilized circuit
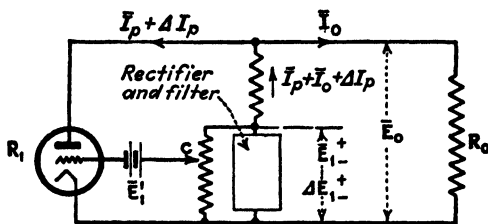
FIG. 8.—Voltage-stabilizing circuit.

varied from 142.7 to 153 when the input voltage changed from 90 to 97 volts.

<div align="center">

TEST DATA

Tube 112-A E_f = 4.0 V

E_0 = 150 volts I_p = 14.8ma.

R = 445 ohms c = 93.8 per cent

</div>

Voltage-doubler Circuits.—It is possible to use two rectifiers in a circuit which will double the voltage output of a single tube, and without the necessity of using a transformer.   Thus from a 110-volt a.c. line a voltage of more than 220 volts d.c. may be obtained.   The circuit is shown in Fig. 9 where two tubes are employed.   In Fig. 10 a single full-wave tube is used, with leads brought out from both cathodes.   High capacities are required, but the voltage they must stand is not great.

[1] KOHLER, H. W., *Electronics*, December, 1934.   On this general subject of voltage regulators see *Rev. Sci. Instruments*, October, 1935, where C. R. Larkin discusses oscillations at 700 to 1,500 cycles which take place in such regulating circuits and cause large voltage fluctuations.

RCA Manufacturing Company sells a voltage regulator in connection with a "B eliminator."

An ingenious circuit utilizing the 25Z5 tube has been developed by Westinghouse for use in a light relay. This circuit is shown in Fig. 11 where it will be seen that one-half of the tube furnishes voltage for the plate of the 43 power tube and the other half furnishes the grid-bias voltage. Were it not for this arrangement, the bias voltage would be subtracted from the total voltage available to obtain the plate voltage which would then be too low to derive much power output.
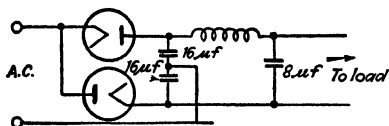
FIG. 9.—Voltage-doubler circuit.

There is another advantage to this circuit. Operating the light relay, the power tube is overbiased so that any change in its grid voltage produces a change in plate current. If the bias for the grid is obtained from a resistance in the cathode lead through which the plate current flows, a variable bias voltage will be obtained as the grid-input voltage (from the phototube or other source) varies. Therefore the bias will change and it happens that the arrangement ordinarily tends to defeat
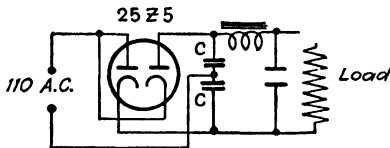
FIG. 10.—Single-tube voltage doubler.
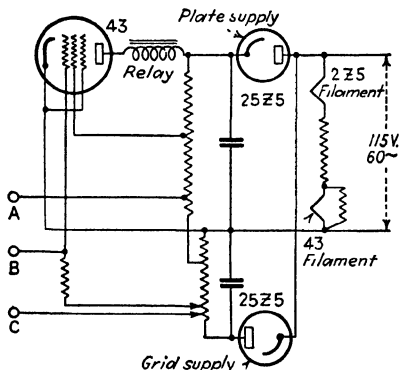
FIG. 11.—Use of 25Z5, one-half to supply plate voltage, the second half to supply grid bias.

its own purpose. The plate current increasing when light strikes the phototube produces a higher voltage drop along the cathode resistance and biases the grid to a still higher negative voltage

which tends to reduce the plate current. Since the relay in the plate circuit needs as much current change as possible to insure positive action, the ordinary circuit tends to circumvent the desired results.

In the Westinghouse circuit (which is really a voltage doubler) the grid bias is fixed since it comes from the second half of the rectifier tube, even though the plate current varies. In the commercial unit the relay is sturdy enough and sufficiently positive in its action to handle 20 amp.
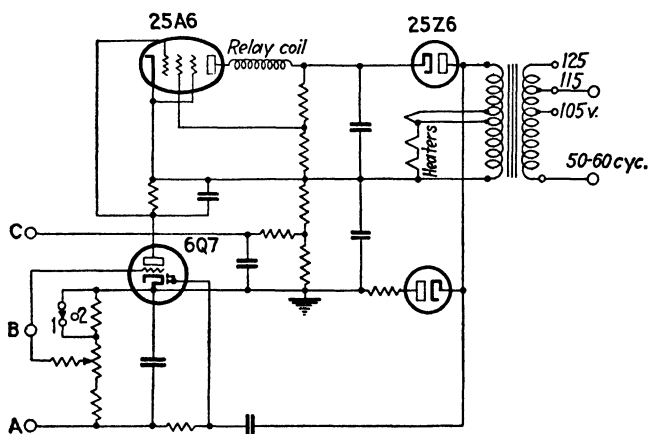
Fig. 12.—Photo-electric relay using voltage-doubling rectifier.

Sensitive Light Relay.—A sensitive light-relay circuit has been proposed,[1] with a pentode and a voltage-doubler tube as a basis and the addition of a duplex-diode high-mu triode tube and its associated circuit. The grid of the high-mu triode is actuated by a phototube connected to *A,B* to have the contactor pick up with incident light or to *B,C* to have the contactor drop out with incident light. One feature of the circuit is the addition of the double diode which rectifies voltage for the triode grid and the phototube circuit. Hence, the circuit may be described as one that triples the voltage, because from a 115-volt secondary over 400 volts of direct current is obtained.

[1] Lenehan, B. E., Meter Engineering Department, Westinghouse Electric and Manufacturing Company, Newark, N. J. This circuit will be found in the chapter on light-sensitive tube applications and is repeated here for convenience.

Grid-bias Scheme.—The circuit shown provides a means of obtaining grid-bias voltage by the use of an extra tube connected as a diode. A type-27 or -56 tube is connected as a diode across one-half of the high-voltage transformer winding which supplies the usual full-wave rectifier tube, the plate of the 56 being connected to the center tap of the transformer through a dropping resistance shunted by a high capacity. The voltage which appears across this dropping resistor may be used for biasing the grids of tubes supplied by the rectifier, the proper voltage being obtained by the potentiometer arrangement shown.

This means of obtaining grid-bias voltage is particularly useful for d.c. amplifiers, since changes in the current taken from the full-wave rectifier do not affect to any great degree the values of bias voltage appearing across the dropping resistor. It is usually desirable to heat the filament of the 56 diode by means of a separate transformer, in order to avoid high voltage across the heater insulation. If fuses are used, however, it is possible to connect the diode heater directly to the common-filament transformer, the fuses acting as a protective device in case the insulation of the heater breaks down.

FIG. 13.—Unusual grid-bias circuit.

A Thermionic Time-delay Relay.[1]—Taking advantage of the negligible leakage of good-grade paper condensers and the resistance stability of good volume controls, one can assemble a simple, inexpensive, highly practicable thermionic time-delay relay for such applications as repeating or cycling life tests in developmental and production-checking work. The equipment described has been used regularly for accelerated life tests on resistors. The time-delay relay offers "on" and "off" timed intervals of from $\frac{1}{20}$ sec. to a full minute; and by adding proper resistors in series with controls R_C (charging resistor control) and R_D (discharging resistor control) longer timed cycles can

[1] MUCHER, GEORGE, *Electronics*, April, 1936.

be obtained. With suitable paper condensers and volume controls, the unit may be readily calibrated to read in time-delay seconds. It operates on 110 volts alternating current, and the operation is not affected by ordinary line-voltage fluctuations.

Because, for economy's sake, a unit to operate without transformer on 110-volt a.c. supply was desired, a line-voltage dropping resistor was chosen. With this requisite in view, series heater-type tubes were selected, viz., a 25Z5 rectifier tube and a 43-power pentode tube. The 25Z5 tube is operated as a voltage doubler (the circuit will not operate on 110-volt d.c. lines) and delivers
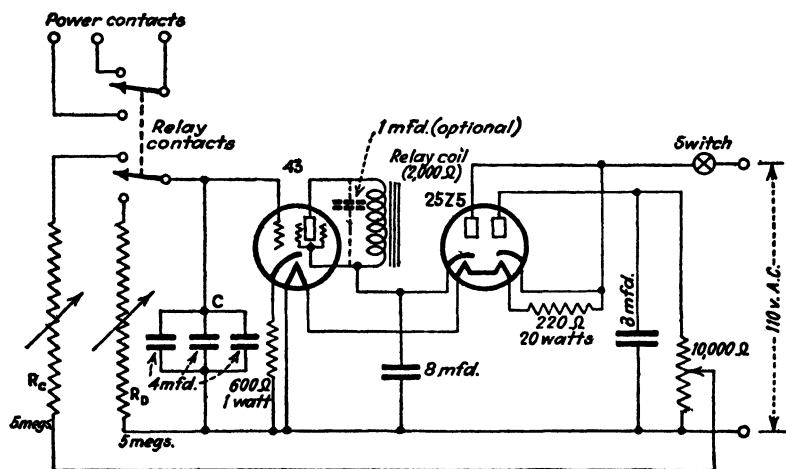
Fig. 14.—Relay interrupter using circuit of Fig. 11.

pulsating d.c. power of 250 volts (approximate). One-half of the rectifier tube supplies the plate power for the type-43 tube which operates the relay. The other half provides a negative bias voltage for charging the condenser C across the grid circuit of the type-43 tube (see also Fig. 11).

Since the charging voltage affects the time-delay constant of the entire unit, a variable charging voltage is employed. This is obtained by means of the 10,000-ohm, wire-wound potentiometer. The accompanying curves indicate the effect of varying the charging bias voltage E_C.

In choosing the values for the charging potentiometer R_C and the discharge potentiometer R_D, high-resistance values were found to give long time delay cycles but rather critical

control on the short cycles. Finally, a compromise value of 5 megohms was decided upon. This value permits reasonably accurate time cycles for both long- and short-time intervals. For time cycles greater than 1 min., extra fixed carbon resistors (about 20 megohms) may be connected in series with the charge and discharge potentiometers R_C and R_D. With such an arrangement time cycles of over 30 min. may be obtained.

It is of prime importance that the grid circuit condenser C be of good quality, with a very high leakage resistance. For
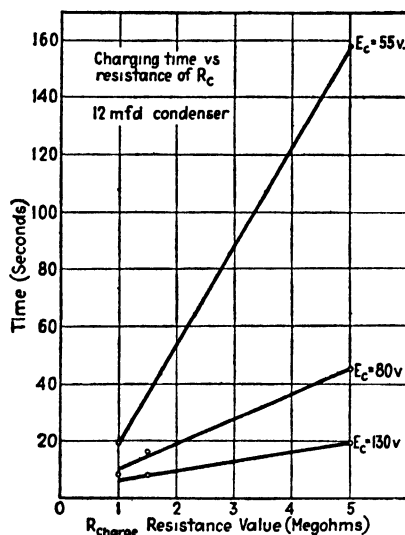
Fig 15.—Charging time as function of resistance.

this reason it must be evident that only paper condensers can be used for this function. Electrolytic condensers obviously have too low a leakage resistance to be considered.

Special consideration is required in the choice of the relay. It must have at least two sets of moving contacts, one controlling the charge and discharge of the condenser C, and the other acting as a power switch for the connected device or load under cycling test. Because of the relatively high impedance of the 43-tube plate circuit, a high-resistance relay winding is necessary for proper power transfer. The relay should operate on a current of between 5 and 30 ma. The particular relay employed in the layout shown has a d.c. resistance of 2,000 ohms

and operates on 5 to 30 ma. flowing through its winding, depending on the armature-spring tension adjustment. Should difficulty be experienced in procuring a relay of proper impedance, a low-impedance relay can be readily rewound with smaller wire, say, of No. 40 B & S gage, serving the purpose. A Western Electric relay or equivalent is recommended for precise operation.

Welder Monitor.—In the manufacture of metal tubes, in which currents as high as 75,000 amp. are used, the welding machines must be adjusted so that the total heat energy developed in the weld during the welding cycle has the correct value. In the RCA Radiotron Division plant this quantity is measured by means of an ingenious circuit designed by F. H. Shepard, Jr.

An air-cored toroidal coil is slipped over one of the welding electrodes where it induces a voltage from the field of the welding current. Because the welding current is a train of sine waves, the coil voltage is sinusoidal and is proportional to the welding current.

FIG. 16.—Circuit of welding monitor.

A small part of the coil voltage, about 0.1 volt, is applied to a diode in series with a condenser. Since the diode characteristic for this small voltage has the form of the square law, the current flowing into the condenser is proportional to the square of the coil voltage and hence proportional to the square of the welding current. The condenser stores up the charge flowing into it and thus builds up a voltage that is closely proportional to the diode current integrated over the welding period. The condenser voltage is not large enough to disturb appreciably the proportionality of the diode current to the square of the coil voltage, and hence the voltage attained by the condenser is proportional to

$$\int_0^T i^2 dt$$

where i is the instantaneous value, and T the duration, of the

welding current.   It will be seen that this integral can be taken as a measure of the total heat energy of the weld $\left(\int_0^T i^2 r dt\right)$ if it is assumed that r, the resistance of the weld, always varies in the same manner during the welding period.   On the basis of this assumption, which is approximately correct, the condenser voltage is read on a vacuum-tube voltmeter as a measure of the total welding heat which is the quantity to be measured.

This measurement is particularly helpful when a welding machine is first being put into operation. There are two adjustments to be made on the machine, one controlling the peak amperage of the welding current and the other the duration of the welding current. These adjustments are made so that the total heat energy of the machine's weld has the same value as that of other machines turning out satisfactory work.

An Electronic Interrupter.— Mechanical interrupters that are operated over wide ranges of frequencies are expensive and large in size. An electronic interrupter devised by Hanly[1] is very inexpensive and occupies but small space. The diagram shows the
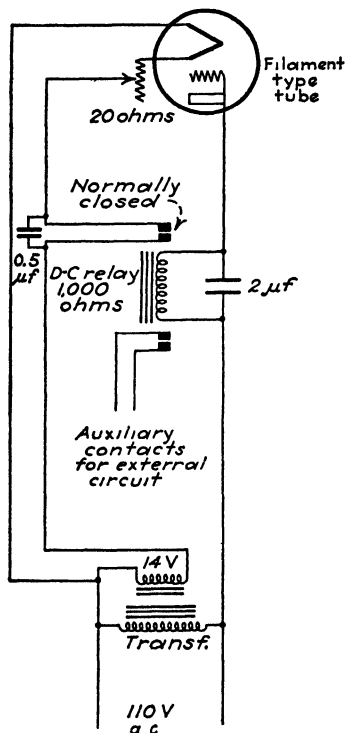
Fig. 17.—Electronic interrupter.

circuit, and its operation is as follows: The plate current of the tube flows through the relay coil, causing the two contacts to open.   When these contacts are opened, the current to the filament is cut off, and the plate current is interrupted.   After the demagnetizing of the relay coil, the contacts are closed again; this energizes the tube filament once more, thus repeating the sequence of operation.

It will be noticed that the filament circuit is energized by a 14-volt supply fed through a 20-ohm rheostat.   The reason for

[1] HANLY, JAMES H., *Electronics*, November, 1935, p. 449.

this relatively high voltage is to give a high-velocity operation to the emitter in the tube. The rheostat gives a fairly complete control of the velocity of operation.

As can be seen from the diagram, the output of the tube to the relay coil is of a half-wave nature. For this reason a relay with a shading coil or one shunted by a condenser is needed. The latter type is used by the writer. The condenser discharges through the relay coil when the tube is going through its inverse operation, thus keeping the armature from chattering. A small, fixed condenser across the filament-break contacts cuts down the wear from pitting; a half microfarad was found sufficient. The auxiliary contacts on the relay can be used to open or close any external circuit.

Hanly states that a 201A-type tube gives impulses of the order of 3 per second at full voltage, while a 281-type rectifier gives impulses of the order of one every 3 sec. and can be caused to produce one interruption every 15 to 20 sec. He has used it as a cable tester and as a tube-emission tester.

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Battery-charger Tubes.—Tungar (General Electric) and Rectigon (Westinghouse) tubes for charging batteries have been in wide use since about 1916. These are two-element (sometimes three-element) gaseous tubes acting as rectifiers purely. They are characterized by a large tungsten filament acting as cathode heated to an excessive temperature in order to make it yield very high emission, about ten times that obtainable in high-vacuum tubes. Enough argon gas is admitted to the tube to prevent evaporation of the filament at this high temperature. This pressure is much higher than that found in other gaseous rectifiers; for example at least 1 mm. Hg. is necessary to prevent evaporation and actually a pressure of about 5 cm. Hg. is used. The life of the filament increases up to this value of pressure.

Magnesium is put into the tube on construction to clean up gas liberated during the life of the tube. The argon must be very pure to prevent certain other gases which ionize and permit the positive ions to bombard and finally to disintegrate the filament. The anode, of large cross section, is made of graphite.

The high pressure in the tube limits the voltage that can be put across the elements, since the sparking potential of argon at these pressures is about 200 volts. The current is limited by the tendency of the arc to concentrate at one spot of the cathode and to overheat it at this point, which will finally cause it to break.

Some means of automatic regulation must be provided to take care of line-voltage variations, variations in tubes, etc. Resistance or reactance in the primary or secondary circuit is the usual form. The resistance or reactance is usually connected into the secondary circuit. For reasons of economy reactance is employed as the regulatory element especially in units of large capacity.

The charging rate may be constant, as in "trickle" charging when a large amount of ballast resistance is used, or it may be tapering, in which case the ampere output drops off as the battery becomes charged. With a small degree of regulation the charging rate will drop off sharply as the battery is charged. Voltage taps on the primary are often used, especially on the larger outfits, to compensate for various line conditions. To change the charging rate, taps are included on the secondary, or if the lower efficiency is not undesirable, a resistance or reactance in the secondary circuit reduces the amperes through the battery.

Many users of battery chargers of this type have discovered that after the arc has been established the filament current can be cut off. Current will continue to flow through the tube. It is believed by those who practice this expedient that greater economy results due to the saving in filament-heating power. The manufacturers, however, state that it is unwise to operate the tubes in this manner since the arc tends to concentrate at some point of the filament and reduces its life. Operation tends to become erratic under this condition of use.

Several terms are used in connection with Tungar and Rectigon tubes. The "pick-up" voltage is that voltage which must be impressed across the tube to start its rectifying action. When current flows, the voltage drop across the tube decreases to become the "arc voltage." The recommended minimum voltage across the tube to insure starting the current flow even under low-line voltage conditions is of the order of 25 to 30 volts. The voltage across cathode-anode which may cause breakdown is called the "flash-over" voltage. On inductive loads the user must be careful that the sum of the inductive kick-back plus the normal voltage across the tubes does not exceed the limits set by the manufacturer.

The tubes vary in current output from the small trickle charger delivering 0.6 amp. to a 6-volt battery to tubes which will supply 30 amp. at 60 volts.[1]

Surge Absorber Tube.—The PJ-20 (General Electric) is a two-element cold cathode tube of the gaseous discharge, voltage regulator type useful where only occasional operation occurs.

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[1] See *Instruments*, January, 1936, for an alternator-voltage regulator using Tungar tubes developed by G. F. Lampkin.

The voltage drop for regulator purposes is about 70 volts; the time of de-ionization very low; the tube will pass instantaneous currents as high as 200 amp., although its average rating is for 0.25 amp.

Ballast Tubes.—These constant-current devices are resistors whose resistance at a certain temperature varies with temperature so rapidly that with varying voltage across the tube the current remains constant. They are not electronic devices in that no electrons are emitted or released from the cathode.

They are used to maintain constant current through a load in spite of variations of applied voltage. They are used to protect the filaments of vacuum tubes against extreme variations in filament voltage; to maintain constant voltage to the tubes of a radio receiver, or transmitter, in spite of line-voltage variations. Since they are not electronic, they will not be described here further. They are in the same category as constant-current or voltage transformers and other forms of nonelectronic regulating equipment.[1]

Electron-tube Ionization Gage.—In the manufacture of electron tubes it is of great importance to have an accurate measure of the pressure within the tube, for example in pumping the tube to determine when this process shall end. There are other cases where it is desirable to have a measure of pressures of the order of 10^{-8} mm. of mercury or lower.

Ionization gages utilizing conventional three-element amplifier tubes have been used for years.[2] They are based on the fact that the production of positive ions in such a tube is directly proportional to the gas pressure if the accelerating potential and the electron current are constant. Thus, with a constant positive voltage on the plate (or grid) of a three-element tube, and a filament at a constant temperature the production of electrons will be constant. On their way to the anode they will collide with ions of gas, the number of collisions and consequent produc-

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[1] Information regarding their operation may be found in bulletins of the manufacturers, General Electric Company, Westinghouse, Amperite Company, etc., and in the following two articles: JONES, H. A., The Ballast Resistor in Practice, *Gen. Elec. Rev.*, May, 1925; and JONES, H. A., Theory and Design of Ballast Resistors, *Gen. Elec. Rev.*, Sept., 1925.

[2] DUSHMAN and FOUND, *Phys. Rev.*, vol. 17, p. 7, 1921; also vol. 23, p. 734, 1924. FOUND and REYNOLDS, *Jour. Opt. Soc. Am. and Rev. Sci. Instruments*, vol. 13, No. 2, 1926.

tion of positive ions, depending upon the number of gas molecules present.

In practice these tubes, now specially made for the purpose, are attached to the tube to be pumped, or to some part of the vacuum system. Gas common to the system is pumped out by various types of pumps now in common use, and as the gas decreases, of course, there will be fewer collisions and a smaller ionization current produced in the pressure gage.

The third element in the tube is made negative with respect to the cathode so that it will collect the positive ions. The current flowing in this circuit is a measure of the gas pressure. The greater the number of collisions per electron, the more sensitive is the tube. One way to increase the sensitivity is to increase the production of electrons, but this is limited by the amount of power the anode can safely dissipate in the form of heat without evolving gas. Another way to increase the sensitivity is to increase the distance the electrons must traverse before they are caught by the positive plate. In increasing sensitivity in this direction there is danger that oscillations of the Barkhausen type may occur.
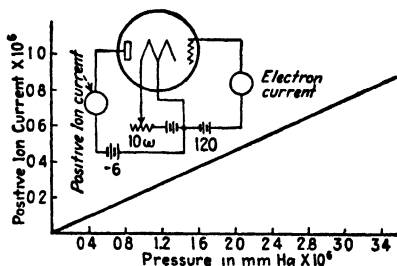
Fig. 18.—Circuit and characteristic of ionization gage.

An ionization manometer of recent type has been described by Jaycox and Weinhart of the Bell Telephone Laboratories.[1] The circuit is shown in Fig. 18 to consist merely in a thermionic cathode, an element maintained positive to collect the electrons and the negative electrode to collect the positive ions. A calibration of the device is shown.

[1] Jaycox, E. J., and H. W. Weinhart, A New Ionization Manometer, *Rev. Sci. Instruments*, vol. 2, p. 401, July, 1931.

A method of determining the combustibility of gas and air mixtures is described in *Elec. J.*, November, 1935, by E. Rutledge Davis: A Wheatstone's bridge has two arms made up of platinum filaments, one hermetically sealed within a glass tube, the other enclosed in a tube open at both ends. The bridge is balanced when the open tube filament is surrounded by pure air. Any combustible vapor drawn into this tube burns on the surface of the filament, changing its resistance and unbalancing the bridge.

Evacuated Resistance Units.—Although not electronic, a series of high resistances sealed in tube envelopes and with tube bases have uses in the electronic art sufficient to make them worth describing here. There are numerous uses for resistances of the order of several hundred or thousand megohms that are stable, particularly in the low grid current tubes of the electrometer and FP-54 types.

Such resistances have been made by Rentschler and Henry[1] by sputtering either carbon or graphite on to a glass spiral in an inert gas. Such resistances are very constant and pass a current strictly proportional to the applied voltage. Wires are sealed into the two ends of the spiral. The glass around the wires is then painted with gold solution such as is used in china painting. This is baked so that the gold makes good contact with the wires and the glass. After mounting, the bulb is exhausted, and then argon at a pressure of about 2 mm. is admitted. Then the structure is heated until the carbon is white hot to drive out occluded gas. This process is repeated several times and finally a fresh supply of argon is admitted and the tube sealed off.

Resistances up to several hundred megohms have been made in this way. They have a negative temperature coefficient of about 0.7 per cent per degree Centigrade.

Glow Tubes.—The characteristics of gaseous-discharge tubes have been described in Chap. IV. If two elements are sealed into a tube which is then pumped and an inert gas admitted at the proper pressure, the current-voltage characteristics become extremely interesting. Up to a certain voltage across the tube no current flows, but when the striking or firing potential is reached, a discharge passes and the voltage across the tube drops and becomes quite constant regardless of the current taken from the tube.

The first wide-spread use of a tube of this type (UX-874) was in early radio receivers operating from alternating current, where it was desired to feed fixed voltages to various portions of the circuit from a supply which had a high resistance and consequently poor regulation. The glow tube was bridged across a portion of the voltage divider of the rectifier-filter system and maintained the voltage of that portion fixed at 90 volts regardless

[1] Improved High Resistance Units, *Rev. Sci. Instruments,* vol. 3, No. 2, February, 1932.

of the current taken off by the tubes drawing power from this source. In those days the voltages usually required were 45 and 90, because of still earlier art when B batteries of these voltages are employed. Therefore the UX-874 was designed to break down somewhat in excess of 90 volts and to maintain the 90-volt potential up to the limit of current permitted by the manufacturers, about 50 ma.

Such tubes must be used with current-limiting series resistance or the tube will be destroyed. The tube employed in radio receivers consists of an inner rod about $\frac{1}{8}$ in. in diameter surrounded by an outer cylinder about 1 in. in diameter and length. The gas is argon or helium. Reich has admitted sodium into the tube and used it as a source of monochromatic light.[1]

The time for the tube to reach the firing potential after a voltage has been applied is very short and is dependent upon the voltage applied. Thus if the potential applied is about equal to the breakdown voltage, the time may be of the order of 100 microseconds. Doubling the voltage applied may reduce this time to 5 to 10 microseconds.

The electrodes are close together and the glow covers an area depending upon the voltage up to a certain voltage and when the plates are completely covered by the discharge, the intensity of illumination becomes a linear function of the discharge current. These tubes are usually neon-filled, but other gases and combinations of gases have been employed. The light emitted from the neon tube is orange red in color and has a luminous efficiency of about 1.2 lumens per watt corresponding to about 10 watts per candle. Often they are used to show whether a circuit is alive or dead.

Applications of the Glow Tube.—Because of the interesting current-voltage characteristic of this tube, it has been put to many uses. For example, current may be allowed to flow, slowly if desired, into a condenser by means of a series resistor. Across this condenser is a glow tube, designed to break down at some predetermined voltage. When the voltage across the condenser reaches this potential, the glow tube passes current suddenly and discharges the condenser. Then it will charge again at a rate depending upon the time constant of the circuit

[1] *Rev. Sci. Instruments*, May, 1930. See also *Physics*, Oct., 1933.

when discharge occurs again. In other words, an oscillator or source of pulsating voltage may be secured in this manner.[1]

The tubes may be used as stroboscopes in studying moving machinery. By design the tube may be more brilliant on one-half cycle of alternating current than on the other, or the current passed may be the same on each half cycle. In the Stroboglow of Westinghouse an additional grid is placed in the tube to control the discharge. Thus it becomes a grid-controlled glow tube.

Neon Ground Test.—The accompanying diagram shows the connections of a neon-tube leakage indicator, which may be used to test production units for the presence of faulty insulation
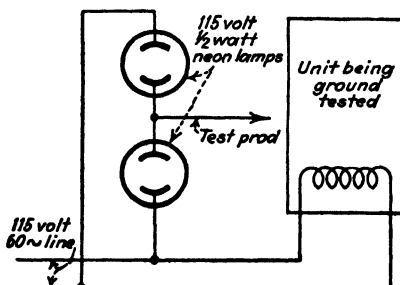
Fig. 19.—Neon lamp ground tester.

and grounds. The neon lamps used are of the half-watt size and must not light at a voltage lower than 75. When used in connection with 115-volt, 60-cycle lines, as shown, it is possible to detect a leakage to ground of 1,000,000 ohms. Two lamps are used in series across the line so that both sides of the line may be checked without reversing the line plug and with the appliance switch on or off. The use of two lamps also eliminates any capacity effect produced by the use of alternating current. If the unit under test is grounded, one of the two lamps will light, and the approximate position of the short circuit in the winding may be found, since the lamp that lights is connected to the side of the line farthest away from the ground.

For more sensitive tests, a single neon lamp of the same type may be used in series with a 50,000-ohm, 1-watt resistor on a 500-volt, d.c. line. With such an arrangement, leakage resistances of the order of 5,000,000 or 6,000,000 ohms can be detected with ease.

[1] See KOCK, W. E., *Electronics*, March, 1935.

The Stabilivolt.—Several electrodes may be placed within the same envelope just as several 874's may be operated in series. The total voltage across the tube is therefore divided into several smaller voltages which may be utilized for various purposes. This German development, like a floating battery, is placed between the source and the load and enables any form of power supply to become a source of constant voltage. The voltage output will fluctuate not over 0.1 per cent with a 10 per cent fluctuation of line voltage. The voltages secured from the several electrodes are independent of each other to an order of precision of 0.01 to 0.02 per cent.

For low a.c. voltages the resistance of the device is very low, of the order of 20 ohms. Thus it performs an efficient filtering function especially at low frequencies where very large capacities would be required to attain an equivalent low shunt impedance.
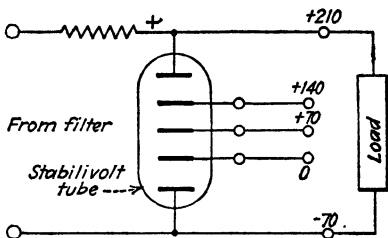
FIG. 20.—Gas tube (Stabilivolt) for voltage regulation.

Neon-tube Contactor.—By placing two electrodes in the proper pressure of neon or other gas, a voltage can be found at which the tube will glow. At this voltage the resistance of the tube becomes much lower than its no-current value. If, once the discharge has begun, the voltage is reduced, a value will be reached at which the tube will cease to pass current. Therefore if the tube is supplied with direct current of the proper potential from a storage source, a condenser, for example, the tube will pass current thereby discharging the condenser which will again charge up until the proper voltage is reached, when another discharge takes place.

The circuit shown in Fig. 21 is taken from Reich[1] and uses a General Electric Type G-10 neon tube; it operates from any source of direct current capable of supplying 30 ma. at approximately 350 volts. This source may be a rectifier-filter system supplied with alternating current from the 110-volt power lines. The arrangement will oscillate at frequencies beyond the ability of a mechanical relay to follow and as low as 1 cycle in

[1] REICH, H. J., *Rev. Sci. Instruments*, March and April, 1931.

many seconds. The capacity of the condenser controls the time frequency of operation, although variations in voltage across the charging tube have an effect on the frequency, too.

The time in the cycle at which the relay operates is controlled by changing the steady current through the relay by variations in the setting of the potentiometer. The relay should close on approximately 2 ma. and open on not much less current than this. This calls for light spring tension and an air gap in the magnetic circuit to reduce residual magnetism. The glow tube should be illuminated to some extent at low frequencies of opera-
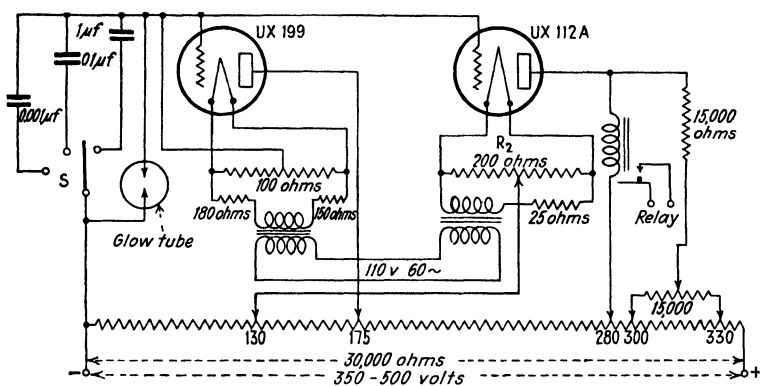
FIG. 21.—Neon-tube contactor using glow tube, condenser, and resistance—a combination often used for time-delay functions.

tion since these tubes are light-sensitive and function at low frequencies better when illuminated.

An estimate of the number of microfarads of capacity required may be had by multiplying the maximum period by 3; but individual neon tubes vary in characteristic and this factor is only approximate.

Suitable relays may be obtained from telephone supply houses, for example, the Western Electric type E-447, or Westinghouse Style No. 695633 have been suggested by Reich.

THE OSCILLATOR OR GENERATOR

One of the most important functions of high-vacuum tubes is that of oscillation or generation of alternating currents from either d.c. or a.c. supply. This ability to generate frequencies of practical value from a few cycles per minute to many millions per second arises directly from the amplifying power of the tube.

Mechanism of Self-oscillation.—Consider the amplifier circuit in Fig. 22. The input and output circuits are tuned approximately to the same frequency, and there is no coupling between the plate and grid coils. A voltage impressed on the grid coil will be amplified and will appear in greater amplitude across the plate coil. Now suppose the plate coil is coupled to the grid coil so that the circuit becomes that of Fig. 23. Now it will be found that an alternating voltage will still appear across the plate coil and current will flow in the a.c. circuits even if the exciting voltage on the grid from an external source is removed. The
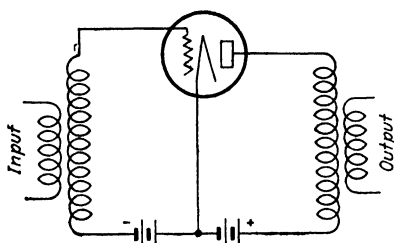
Fig. 22.   Fig. 23.

Fig. 22.—Amplifier deriving exciting voltage from external circuit.
Fig. 23.—Amplifier which becomes self-excited—it oscillates.
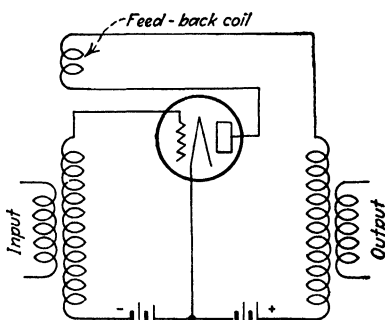
circuit is *oscillating* or generating oscillations of a frequency determined by the circuit inductance and capacity.

What happens is as follows: in the amplifier some of the output voltage appearing across the plate coil is fed back into the input exactly as though it got there from an external circuit. There are losses in this circuit as well as in the plate circuit but if the amplification is sufficient to make up for these losses and have some power left, this power will appear as self-oscillations.

Suppose, for a purely theoretical case, it requires 1 mw. to excite the grid from an outside source, as from another circuit, and that the tube has a power amplification of 100 times. Therefore 100 mw. appear in the plate circuit. If the losses in plate and grid circuits amount to 50 mw., there remain 50 mw. that can be used for some other purpose. When the plate coil is coupled to the grid, some of the output voltage excites the grid and if in the proper phase to add to the original exciting voltage,

this new additional voltage will be amplified and some of it will again be returned to the grid circuit. Finally this process builds up to the point where all the losses are wiped out by the output power and the tube continues to oscillate.

Building up oscillations is practically instantaneous in ordinary circuits. It may take but a few cycles to arrive at a stable condition and since the frequency can be as high as a million cycles the actual time of building up is very small. In general the direct plate current of an oscillating tube differs from that taken by the tube when it does not oscillate. This is a very important fact since the change in plate current between oscillating and nonoscillating conditions may be sufficient to operate a relay.

An oscillator is simply a self-excited amplifier, and is analogous to a self-excited generator. Theoretically, oscillations cannot start unless some disturbance starts in motion the first cycle of grid voltage which is repeated in the plate circuit but there are plenty of disturbances. All that is needed is to snap on the plate voltage or to shake the tube. It is possible to design and to build circuits in which oscillations build up slowly and not without considerable provocation, but in general amplifying systems are too willing to oscillate and considerable pains are taken in high gain systems to keep the entire set-up of apparatus from "winding up" into continuous oscillation. In this condition no amplification of outside signals can take place because the system is thoroughly overloaded with its own excitation.

Coupling from output to input may take place in many ways. The simplest to understand is that described above. The capacity existing between grid and plate within the tube acts as a coupling impedance and may be sufficient to pass back to the grid circuit enough of the plate-circuit energy to cause oscillations. The plate-circuit voltage may be coupled to the grid by capacity, inductance, or resistance, or combinations of these impedances.

The grid may be biased negative just as in an amplifier. The tube may supply its own bias by the usual method of letting plate current flow through a resistor, or the bias may be obtained as shown in Fig. 24. Here a resistance is in the grid circuit. It is shunted by a condenser large enough so that no impedance exists to the flow of current of the desired frequency. When the

tube oscillates, its grid is driven positive on half the cycles of feed-back voltage.   When the grid goes positive it draws current. This current flows through the resistance and therefore a voltage drop appears across it.   This voltage is of such a polarity that the grid is made negative with respect to the filament.   Thus the grid biases itself.

In this case the plate current is less when the tube oscillates than when the tube does not oscillate.   Therefore there is less power to dissipate on the plate and the tube will run cooler.   In such a circuit it is of vital necessity to keep the tube oscillating at all times.   If a large power tube, which may generate a kilowatt of power, ceases to oscillate, the plate may become red hot and finally melt.

There are many types of oscillating circuit.   To date, however, the generator has not come into wide use in industrial applications, although in scientific laboratories the oscillator has found many uses.   Therefore the many circuits for producing oscillations, methods of stabilizing the circuits or of producing very high or very low frequencies, etc., will not be discussed here.   They belong almost exclusively to the communication art, and excellent descriptions will be found in books and periodicals dealing with radio communication.

Fig. 24.—Oscillator with grid biased negative by grid current flowing through grid leak.

The general conditions for oscillation or generation are first, the tube plus the circuit must be able to amplify power sufficiently to wipe out the losses in the system; secondly, the output must be coupled back to the input in the proper phase and amplitude to maintain oscillations.

Heterodyne Oscillator.—If the output of two oscillators or generators differing slightly in frequency is turned into a device which does not have a linear relation between input and output, a curious and important phenomenon takes place.   For example, suppose the output of a 1,000-cycle oscillator and that of an oscillator operating at 1,100 cycles are added together in a nonlinear detector tube.   At some instants the two voltages are adding and later on they get out of phase and subtract.

If the output of the detector is put into a pair of headphones or a loud-speaker, not only will the original frequencies be heard but their sum and difference. Thus there will be present in the output, 1,000, 1,100, 2,100, and 100 cycles.

Much use is made of the phenomenon in radio circuits (the superheterodyne owes not only its selectivity but its sensitivity to this circuit) but it is useful for noncommunication purposes. For example, it may be desired to note variations in some function, say the level of water in a tank. The height of liquid may vary the frequency of an oscillator. This output, "beat" with or added to the output of a standard and fixed frequency, will give rise to a lower frequency, so low in fact that it can be made to operate a meter.

The difference between the beating frequencies is called the *beat* frequency. By means of the phenomenon of beats the ear can detect differences in amplitude or frequency much lower than can be heard by other means. For example, if a 1,000-cycle note is caused to vary cyclically in amplitude at a few cycles per second, the ear will hear a rhythmic rise and fall of the 1,000-cycle note. It would be impossible to hear a frequency of variation this low in any other way.

General Electric Elevator Control.—One of the best examples of the use of an oscillating circuit for the control of power is the manner of leveling elevators developed by General Electric. The essential circuit is shown in Fig. 25, and is seen to be that of a grid-leak oscillator.

The various devices comprising a single tube, the necessary coils, condensers, etc., are mounted in a single box termed a pliotron unit. This unit is carried by the car, and as the car approaches the proper floor, a stationary vane mounted in the hatchway is brought between these coils by the movement of the car, thus shielding them from each other. This shielding removes the feed-back voltage from the grid circuit. The tube thus ceases to oscillate, and the plate current goes through a change of approximately 15 to 1. This change in current operates a relay which in turn controls the elevator motor. The circuit oscillates at 200 kilocycles. The vane enters the space between the plate and grid coils, and at approximately the center line of the coils a maximum movement of $\frac{1}{8}$ in. is required to cause the relay contacts to open or close. As the car movement

varies directly as the position of the vanes, a movement of the car of ⅛ in. maximum is sufficient to cause the control to function.

The number of tubes required by any elevator installation varies from one to seven, depending upon the operating refinement desired. Three tubes are usually employed where simple automatic leveling is the only requirement.

The same tubes are employed in this circuit as are employed in railway signal work where approximately some 12,000 such tubes are carried by engines for automatic signal service. The tubes in this signal work have an average life of approximately 3,000 hr., as elevator service is much less rigorous than railway
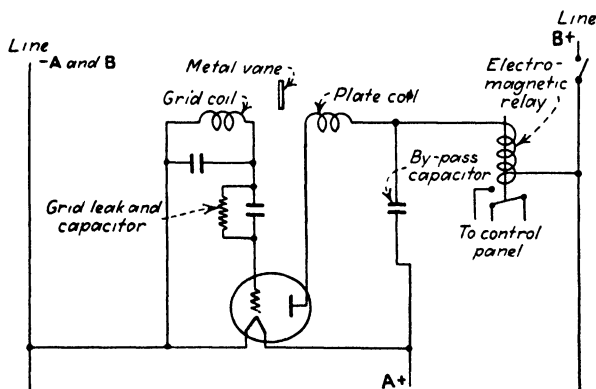
Fig. 25.—Use of oscillating tube for elevator leveling.

service; and as the tubes are operated at a lower rating, the average tube life in elevator service is approximately 12,000 hr. They may, therefore, be considered as reliable as necessary. The filament in such tubes is much heavier and in much less danger of breaking than the filament of an incandescent lamp; furthermore, the temperature at which this filament runs is less than in a lamp, all of which tends in the direction of reliability for the vacuum tube. Even if the tube fails or wears out, the elevator automatically comes to rest near a floor and can be manually controlled until the tube is replaced.

One example of the use of very high frequencies bears discussion. This is the ability to raise the temperature of an object placed in the field of two condenser plates connected to the tuned circuit of an oscillator working at wave lengths of the order of 10 m. and below. Purification of water, cure of diseases that

require the body temperature to be raised to the fever point, killing of bacteria and parasites on plants—all of these applications have been made and will become of greater industrial importance as time passes.

Fault Locator.—The use of a varying-frequency a.c. current, to determine the location of grounds and of open and short circuits in power-transmission lines, has been made by the Pennsylvania Water and Power Company. An oscillator and amplifier capable of supplying frequencies from 1 to 100 kc. are connected to the faulty line, and frequency increased while
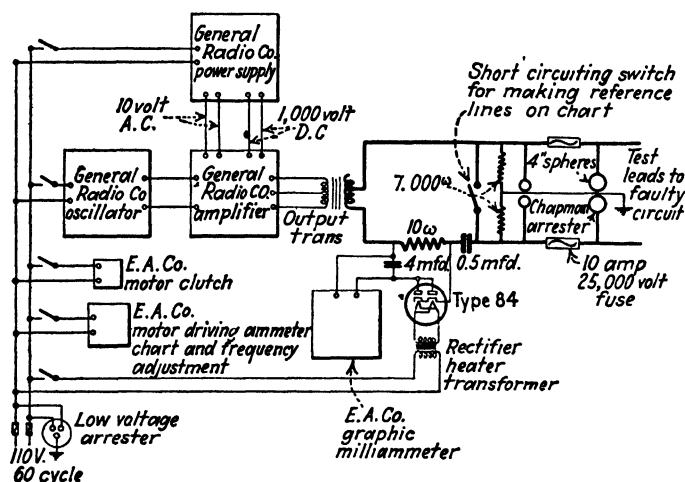
Fig. 26.—Transmission-fault locator. Variable-frequency voltages are impressed on the line. Frequencies at which maximum and minimum currents flow indicate distance to fault.

the current in the line is recorded on a graphic milliammeter, which automatically records variations. It will be found that sharp current peaks occur at equally spaced intervals as the frequency is increased. The frequency interval is then a measure of the distance from the application of the voltage to the fault, expressed by the formula $L = V/2d$, where L is the distance in miles, V is the wave propagation in m.p.s. (determined for each circuit by test), and d is the average difference in frequency between current peaks. By means of such measurements the accuracy of location in most cases can be made within 2 per cent. The cause of the current peaks is the reflection and phase shift which the alternating current undergoes at the fault in the line,

the result being that certain frequencies are reinforced by the reflection, while certain others suffer destructive interference. In the apparatus used the entire oscillator-amplifier, power supply, and recording instruments are mounted on a portable truck containing all the necessary apparatus.

Oscillator for Telemetering.—A system devised by E. G. Watts[1] of the Pittsburgh Equitable Meter Company, for remote indicating the pressure and other conditions peculiar to gas, water, and oil storage, uses an oscillator generating a variable frequency which acts upon a receiver at a remote point which is independent of voltage variations. Several receivers can be
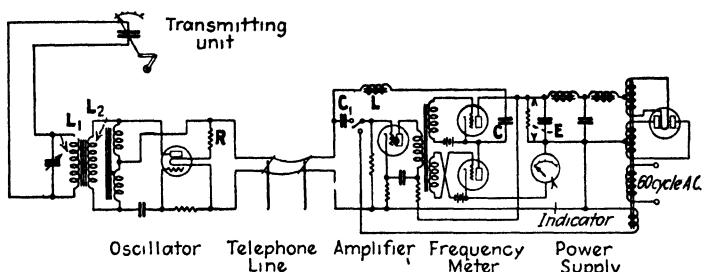
FIG. 27.—Telemetering circuit using variable frequency.

operated from one transmitter. Power for the oscillator is supplied from the receiving end of a telephone line.

Other Oscillator Applications.—A very interesting use of the oscillator may be made by attaching an antenna wire to a portion of the oscillating circuit. Any object approaching this wire changes the oscillatory period, or it may even stop the tube from oscillating, with consequent change in plate current. In the automobile plant, for example, spray painting has been accomplished automatically by such a system in a place where a light-beam phototube method would fail because of the atmosphere of paint which quickly fouls the light source and phototube.

It has been found that certain chemical reactions will take place when under the stimulation of very high mechanical oscillations, whereas they would not occur at the same temperature or pressure without such stimulation. Thus the need for ultrasonic (inaudible) frequencies has arisen. While any oscillator can be made

[1] *Electronics*, February, 1935.

to generate power at practically any useful frequency, much use is made of *magnetostriction* oscillators for this purpose. Gaines[1] has reported on a sterilizing effect of such oscillations, and others have reported on the ease of making emulsions.

In magnetostriction oscillators, the feed-back between grid and anode circuits is supplied by coupling the inductances of these circuits by a metal rod whose natural frequency is that of the electrical circuit. The rod is placed within the grid and plate coils. It makes a good coupling device for transferring energy from the oscillator to the chemical liquid or solid which is to be affected by the oscillations. Gaines's circuit is shown in Fig. 28.

Artificial Radioactivity by Bombardment.—By bombarding certain elements with high-velocity particles such as protons or deuterons, these elements may be made radioactive. Lawrence and Livingston, in the University of California,[2] have developed a method for producing these

Fig. 28.—Circuit of ultrasonic wave producer.

energetic particles with the use of excessively high voltages. Electrons are caused to pass through a series of hollow electrodes, a relatively low potential source being connected at the proper instants to these two electrodes between which the particle happens to be. The final energy of the particle, therefore, is equal to that obtained from a single fall across the potential of

[1] GAINES, NEWTON, *Phys.*, November, 1932.

GAINES, NEWTON, and LESLIE A. CHAMBERS, Some Effects of Intense Audible Sound on Living Organisms and Cells. *J. Cellular Comparative Physiology.* Vol. 1, No. 3, June, 1932.

CHAMBERS, LESLIE A , Soft Curd Character Induced in Milk by Intense Sonic Vibration, *J. Dairy Sci.*, vol. 19, No. 1, January, 1936.

[2] LIVINGOOD, JOHN D., *Electronics*, November, 1935, p. 421. See also LIVINGSTON, M. STANLEY, The Magnetic Resonance Accelerator, *Rev. Sci. Instruments*, January, 1936.

the source multiplied by the number of times that this has been applied.

Electronic Ultra-micrometers.—By means of the tuned circuit and either vacuum-tube voltmeter or oscillating tube, it has been possible to measure distances and displacements of the order of a millionth of a centimeter.

The method is intrinsically simple. It involves the change of capacity of a condenser with change in separation of its plates.
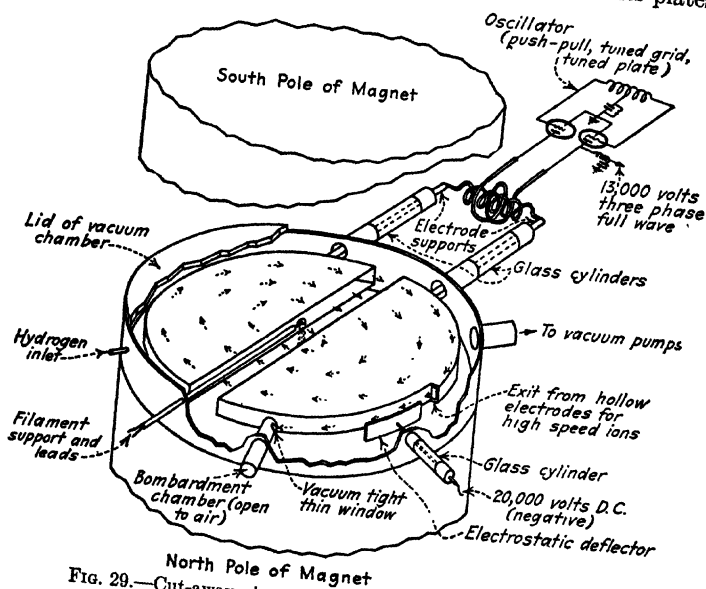
FIG. 29.—Cut-away view of acceleration chamber of Lawrence.

For example, a parallel plate condenser has a capacity equal to

$$C = 0.0885 \frac{KA}{d} \mu\mu f$$

where $K = 1$ in air.

A = area of one plate in square centimeters.

d = distance between plates in centimeters.

Any change in d involves a change in C. Thus if one of two plates is fixed and the other is moved, the capacity changes accordingly.

If the condenser is connected to an inductance through a current meter and the inductance is coupled to a source of alter-

nating current of such a frequency that the circuit is resonant, the current flowing through it will be very sensitive with respect to changes in the capacity. Thus at resonance the current will be a maximum, and if the circuit resistance is low, the current at any other value of capacity will be much lower.

All that is necessary is to tune the circuit to resonance, and let the variable plate of the condenser vary its position with respect to the fixed plate. The change in oscillating current is an indication of the change in capacity and therefore of the displacement of the two plates with respect to each other.

In this case the electron tube is not necessary except as it is the simplest manner of generating the desired frequency with
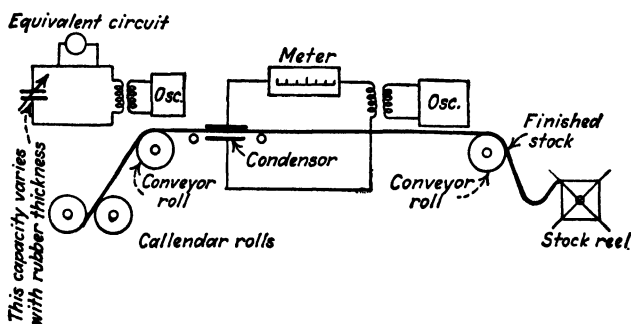
Fig. 30.—Circuit used to measure or control thickness of rubber or other sheet.

which to tune the circuit. In other methods the tube plays a more intimate rôle.

Measurement or Control of Moisture.—By a slight modification the ultra-micrometer may be used to continuously indicate the amount of moisture in newsprint manufacture. When a rayon ribbon is held above a moving sheet of newsprint, the ribbon's length varies with the moisture content of the paper. One end of the ribbon is fixed, the other end is attached to the movable plate of a condenser. Then, as the percentage of moisture in the paper varies, so does the length of the ribbon. These minute changes of ribbon length are indicated by the meter of the ultra-micrometer, which is calibrated directly in per cent of moisture content.

Publishers demand a certain percentage of moisture left in the paper when manufactured, to give it the characteristics desirable for high-speed printing. In paper mills where production may

run 600 tons a day, it is a costly waste to dry the paper more than is necessary. The condenser ultra-micrometer guards newspapers against being too wet to print clearly—or too dry for going through a high-speed press without tearing.

The condenser micrometer oscillator permits continuous measurement to extremely fine dimensions. Furthermore the oscillator makes it possible to measure and control a product without contacting or disturbing that product.
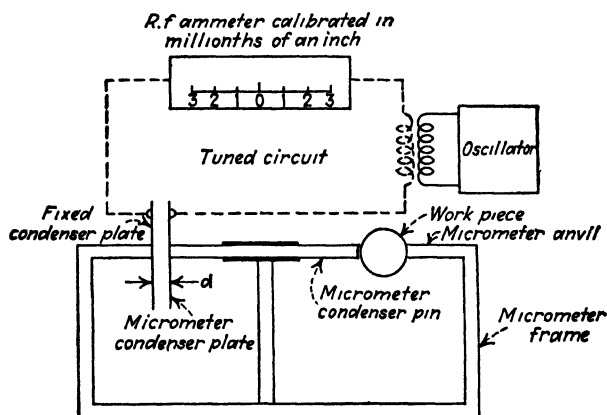
FIG. 31.—Electron-tube micrometer using oscillating circuit.

Thus in Fig. 31 the circuit is coupled, as before, to a generator, and a vacuum-tube voltmeter is placed across the inductance. The voltage across this circuit varies when the condenser capacity is changed. Because the tube puts less of a load on the circuit (introduces less resistance in it) than a current meter, the circuit tunes more sharply so that smaller displacements will cause larger current changes.

In Fig. 31 the tube and circuit are oscillating. The direct plate current taken by the tube, over a certain range, is linear with respect to the frequency of oscillations. Thus if the condenser variable plate changes its position, the frequency of oscillation changes and therefore the steady plate current. In this case all that is necessary is a d.c. meter. A bucking arrangement to keep the original plate current from the meter makes the system more sensitive. Then all the meter registers are changes in plate current.

Obata has applied the method, with some variations, to measurement of seismograph vibration, internal-combustion motor pressures, and the measurement of acceleration. He has indicated that with an initial air gap in the condenser of 0.5 mm. a displacement of 0.00077 mm. will cause 1 mm. deflection on a galvanometer of suitable range. If the initial air gap is decreased, the sensitivity is increased since any increment in air gap will be a greater percentage change than if the initial gap were greater. Thus if the gap is 0.06 mm. wide, a displacement of only 0.00002 mm. causes the 1 mm. deflection.

The limit of sensitivity reported by Obata was little smaller than four hundredths of a millionth of an inch (less than 10^{-6} mm.). Others have amplified the current or voltage changes and observed them in an oscillograph. There are other variations.

In the ultra-micrometer developed by the Atlantic Precision Instrument Company the tube acts as its own rectifier passing current and oscillating only when the plate is positive. Therefore no power-supply apparatus is necessary, the unit being self-contained and rugged, simple to operate, compact, and reliable.

One plate of the caliper condenser is physically fixed. The other plate, left movable, is attached to the back of a micrometer contact arm. Any movement of the micrometer contactor changes the spacing of the condenser plates, changes its capacity and impedance. As the current in the circuit changes with the change of the condenser impedance, a meter measuring this current can be calibrated directly in terms of distance moved by the micrometer contact pin.

Suppose the piece inserted in the micrometer is a standard gage of 1 in. diameter. The circuit is adjusted to bring the meter to center scale, and the spacing of the condenser plates to give a 1-in. meter deflection for every millionth inch change in plate spacing. Then the standard gage may be removed and in its place is inserted a gage to be compared with the standard. The meter will then read by how many millionths of an inch this gage deviates from exactly one inch. The device can be set for any standard spacing and the deviation of the measured piece from that standard measured easily to millionths of an inch. It thereby provides an ultra-micrometer of unlimited range and remarkable sensitivity.

Measurement and Control of Thickness.[1]—The variation in capacity of a condenser, as a material of varying thickness is passed between the condenser plates, has been made use of by the Foxboro Instrument Corporation (see Fig. 30).

For example,[2] rubber produced in a continuous sheet is passed between plates of a condenser. Then as the thickness of the
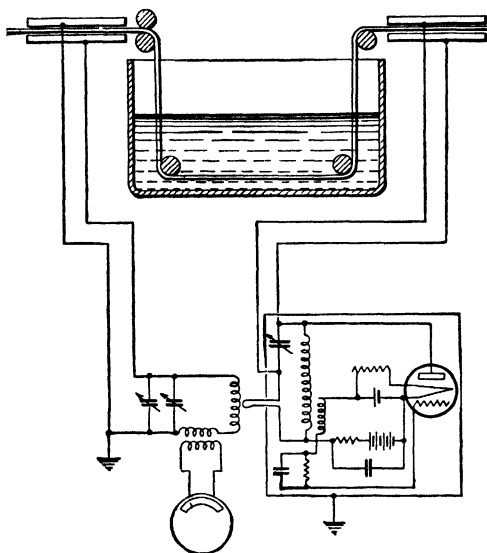
FIG. 32.—Method for measuring material taken up by a treated web (U. S. Patent 1,895,118).

rubber sheet varies, so does the capacity of the condenser because of varying dielectric constant K, and consequently its impedance. The changing impedance changes the current in the tuned circuit to which the condenser is connected. A meter measuring this current thereby indicates directly the thickness of the rubber sheet.

[1] The literature on measuring length, etc., by oscillating circuits is voluminous. Of the early work, that of Whiddington in *Phil. Mag.*, Nov. 20, 1920, used changes in frequency. Dowling in *Proc. Royal Dublin Soc.*, vol. 16, No. 18, 1921, used changes in amplitude of an oscillatory circuit.

PRYTHERCH, *Jour. Sci. Instruments*, April, 1932, described a new form of Dilatometer. Continuous records were obtained when metal specimens of 1–2 cm. long and 7 mm in diameter were heated.

See DANA, D. W., *Rev. Sci. Instruments*, vols. 5, p. 38: 41, January, 1934.

[2] OLKIN, H., *Electronics*, Oct., 1931.

There is no moving contact element in this gage to wear out and introduce error. Nor does the gage touch the rubber when measuring it. Moreover, it does not disturb the normal schedule of operations in producing the sheet, for the condenser is placed along the path of the sheet wherever desirable, and the rubber is gaged when passing through the condenser, while going from one operation to the other.

All the simplicity and convenience of this condenser method of gaging are so much the more remarkable because the dimensions measured are so small and the accuracy obtained so great. This machine easily measures, to 0.0001 in., the thickness of a rubber sheet, whose entire thickness is about 0.0013 in.

Foxboro guarantees to hold paper to a moisture content to within one-half of 1 per cent by this type of equipment.

Temperature Measurements by Oscillating Circuit.[1]—Utilizing the expansion of a chamber into which a hot body is dropped, a method of measuring temperature by an electronic colorimeter has been devised. The chamber is made part of a condenser circuit; variations in the diameter of an 8.5-cm. diameter copper cylinder of 0.00014 cm. per degree Centigrade produces an audible change in pitch in a beat-frequency oscillator working at 30 meters wave length. A change in temperature of 0.003°C. produces about 10 cycles change in the beat note.

Recording Wire Diameter.—Apparatus for measuring wire diameter in process of manufacture has been developed by Loeber and Samson[2] of the Osram Company, London. The electric circuit is that of the heterodyne oscillator described on page 491. One oscillator is fixed in frequency; the frequency of the other is made to vary with variations in the wire diameter. The beat note between the two frequencies is recorded, the changing pitch being an indication of the variations in wire size. The output of the oscillators passes to suitable amplifiers whose input is bridged by a resonant circuit. The latter is so adjusted that the voltage drop across the grid of the first amplifier bears a linear relationship to the frequency variations of the beat note. A recording milliammeter is used in the plate circuit of the amplifier.

[1] ESSER, H., and W. GRASS, *Arch. für Eisenhüttenwesen*, vol. 6, pp. 353–357, 1933.

[2] LOEBER, C. W., *Electronics*, May, 1930.

Dynatron-oscillator Flaw Detector.—An interesting application of a beat-frequency oscillator system made up of two dynatron oscillators has been made by General Electric in a device for detecting cracks in wire and tubing. In this case, where visual detection of small defects is a very slow process requiring extreme care, and often, unfortunately, is inadequate, the wire or tubing is made to pass through the field of one of the oscillators, and defects are caused to make an audible sound, operating a control process by means of a tube acting as a relay.

Eddy currents are set up in the specimens which do not vary if the specimen is uniform. If, however, a crack appears, the eddy currents change, caused by a change in resistance, and the frequency of one of the two beating oscillators is changed. This change in beat note is audible in an amplifier and loud-speaker system so that the operator can note when a flow is present.

In practice the wire, or tubing, is inserted in one or both of the test coils, and the two oscillators are brought to the same frequency by a simple adjustment. Thus no sound comes from the loud-speaker. Then the wire is pulled through the coil and any change in its resistance will vary energy absorbed from the oscillator and hence will change its frequency. The difference in frequency between the two oscillators becomes audible from the loud-speaker.

Either one or two coils can be used. If a single coil connected to only one of the oscillators is used, gradual changes can be detected in the characteristics of the material under test. If a coil from each oscillator is used, the uniformity of the material produces the same effect in each oscillator, and the system remains balanced; but a difference in one end of the wire passing through one of the coils will produce the audible or control effect.

Originally designed to detect longitudinal cracks in tungsten or molybdenum wire, the device has found other applications, the testing of copper tubing, for example.

Bibliography on Oscillation

The literature on the subject is extremely voluminous. The following bibliography is chosen from the same sources which supplied much of the preceding material on other electron tubes and circuits.

WHITE, W. C., Producing Very High Frequencies by the Magnetron, *Electronics*, April, 1930.

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MEGAW, E. C. S., Electronic Oscillations, and Investigation of the Magnetron Short-wave Oscillator, *Inst. Elec. Eng.*, London, Jan. 4, 1933.

TERMAN, F. E., Resistance Stabilized Oscillators, *Electronics*, July, 1933. The work described here has been put to use in the McMath-Hulbert Observatory of the University of Michigan where an oscillator drives an equatorial telescope. See vol 5, No. 10, *Publications of the Observatory*. U. S. Patent No. 1,920,573, E. D. McArthur, Electric Heating Apparatus.

MILLER, C. W., and H. L. ANDREWS, Constant Frequency Oscillator, *Rev. Sci. Instruments*, May, 1930.

Capacity or Charge Effects.—Numerous applications have been made of the fact that the grid of a triode accumulates electrons which make it negative with respect to the cathode unless these carriers are permitted to drain off to a more positive part of the circuit, the cathode, for example. Under this accumulation of negative electricity, the plate current decreases. If, now, the grid is discharged suddenly by connecting it to the cathode, for example, the plate current will increase sufficiently to operate a relay.

If the grid is connected to a large plate insulated from the cathode, this plate may protect a jewel case, a window, or an entire property (if the plate is made in the form of an insulated wire stretched about the property to be protected). Any object approaching this insulated conductor changes the voltage of the grid and causes a plate-circuit relay to operate and ring an alarm. The relay described below is a good example.

Capacity Relay.—Figure 33 shows a new and simple form of capacity-operated relay which can be made up cheaply from standard radio parts.[1]

[1] SHEPARD, F. H., *Radio Club Am., Proc.*, June, 1935.

In this circuit operating on the a.c. line, the sensitive element consists of a pentode oscillator, the feed-back of which is determined by the difference in the ratio between the inductances of the two parts of the oscillator and the ratio between C_1 and the antenna-to-ground capacity. Thus the intensity of oscillation of the oscillator varies with a change of C_1 or a change in the antenna-to-ground capacity C_2. As the cathode of the oscillator is at a high-frequency potential, and as the control grid of the output tube is by-passed for high frequencies through suitable by-pass condensers to the cathode, a negative d.c. voltage equal to the peak radio-frequency voltage on the cathode of the 6J7
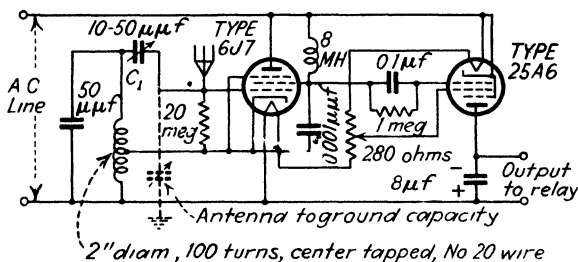
Fig. 33.—Capacity relay of Shepard.

will be across the grid leak and condenser owing to the rectifying action of the grid of the 25A6 output tube and will thus appear on the grid of the 25A6 output tube. The 6J7 oscillator oscillates at high frequency on one-half of the a.c. cycle and builds up the foregoing negative charge on the grid of the output tube. During this time the output tube has negative plate voltage and so is nonconducting. On the other half of the a.c. cycle the 6J7 oscillator has negative plate voltage and so ceases oscillating. The negative charge built up on the grid of the output does not have time to leak off during this interval and hence is effective in controlling the plate current of the output tube, the plate voltage of which is positive during this interval.

This type of circuit finds its application in connection with door openers, counters, etc. and has even been used as a foul-line indicator for bowling alleys.

Relay Tubes.—Instead of a capacity effect, the effect of heat or moisture may be utilized to trigger off the relay in the plate

circuit. (See U. S. Patent 1,900,596 to Whitney, in which relatively small changes in the capacity of the grid circuit of a vapor tube render the tube completely conducting.)

Various types of mechanical relays or circuit breakers have been built within evacuated walls. For example, Ruben (U. S. Patent reissue 18,713) has utilized the thermal expansion of a cathode or anode to close a pair of contacts within the envelope. Prince (U. S. Patent 1,919,987, etc.) among others has sealed two electrodes within the envelope normally in contact. But the lead of one is brought out through a glass structure which permits moving the electrode away from contact with the other without admitting air or gas into the tube. Thus the contact may be broken in vacuum. A mechanical relay of this type has been put on the market by Burgess which will break 10 amperes at 110 volts when actuated by the movement of the armature of an ordinary telephone-type relay in an amplifier plate circuit.
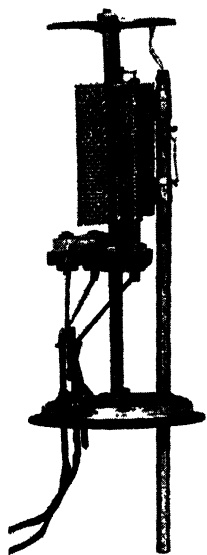
The ZP-186 is a two-element, all-metal, high-vacuum tube. The cathode may be a coated ribbon or a coated plane equipotential surface with separate heater. The anode consists of two plane surfaces parallel to the cathode and mounted on a steel rod extending through a flexible diaphragm at one end of the tube.

FIG. 34.—ZP-186.

The anode may be moved parallel to the cathode surface from outside the tube. This motion changes the available anode area linearly with respect to deflection. The plate current which is a function of plate area also changes linearly with external deflection.

This tube may be used as a measuring device directly to gage small distances, or it may be used in conjunction with other apparatus to perform many duties such as pressure telemetering, temperature control, or automatic weighing.

Deflecting the anode arm 0.001 in. at a distance of 1.0 in. from the end of the tube will cause a plate-current change of 10 ma. This sensitivity is obtained with an anode potential

of 100 volts. The tube is enclosed in a steel cylinder 1.24 in. in diameter and 4.0 in. long. This tube is, as yet, experimental and is not available commercially.

CATHODE-RAY TUBES

One of the most useful of modern electron-tube tools is the cathode-ray tube and the oscillograph made with its use; it enables the engineer or scientist to see, or to record, what transpires in an electrical or other apparatus in extremely short passages of time. It is an old tool, one which has played a tremendously important role in the study of what constitutes matter; more particularly its use in the hands of scientific explorers of a generation ago led to the discovery of the electron,
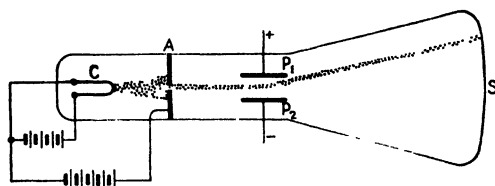
Fig. 35.—Fundamentals of cathode-ray tube.

and to a successful study of the characteristics of this invisible, almost immeasurable building block of nature.

The Modern Cathode-ray Tube.—In its simplest form the tube is shown in Fig. 35, where some of the electrons emitted from the cathode C are drawn to the anode A and pass through the small hole in A down the length of the tube. This pencil of electrons getting through the hole in A, which is called a cathode ray, hits the screen S at a certain point and causes a luminous spot to appear at that point, because the screen consists of a layer of fluorescent materials. One can see where the ray ends.

The ray can be deflected vertically by the plates P_1 and P_2, for if P_1 is charged positively with respect to P_2, the electrons will move upwards while they are passing through the electrostatic field between the plates. And after they have emerged from the field, their velocity will have an upward component which displaces the light spot from the normal central position on the screen. If another pair of deflecting plates is built into the tube so as to impose a horizontal electric field transverse to the ray, the resultant of the two deflections due

to the two fields can be made to have any magnitude in any direction, and the spot can be positioned anywhere on the screen.

The same end can be accomplished by the use of two sets of coils applying a transverse magnetic field to a limited region in the path of the electrons. It should be noted that, unlike electrostatic deflection, a vertical magnetic field will cause a horizontal deflection and vice versa. But the vertical component of deflection depends on the current in one set of coils and the horizontal depends on that in the other; thus the light spot can be moved to any position as before.

It can be shown by theory and experiment that the magnitude of a deflection of the ray is proportional to the intensity of the electric or magnetic field producing it. We have then a light spot which can be deflected in two dimensions and whose deflections are a measure of the voltage at the deflecting plates or current in the coils. This obviously qualifies the tube as a curve drawer for any phenomena that can be translated into a voltage or current. For instance, the voltage across some peculiar resistance like a gas tube is applied to give a horizontal deflection of the spot and the gas-tube current is sent through a set of coils which move the spot vertically. Then as the voltage is varied, the spot moves along a path which shows the gas-tube resistance, breakdown voltage, and so on.

This is an example of curves in which two electrical quantities are plotted against each other. But it is in plotting one quantity against time that the cathode-ray tube is most helpful. For it takes such a short time for the electrons to travel from the region of the deflecting field down the tube to the screen that the position of the spot follows variation in the deflecting field almost instantaneously. This can be shown by computing the velocity of the electrons in the beam. When they emerge from the aperture in the anode, their kinetic energy must equal the potential through which they have fallen. Hence

$$\tfrac{1}{2}mv^2 = eV,$$

where m is the mass, v the velocity, and e the charge of the electron, and V is the accelerating potential. Solving for v,

$$v = \sqrt{2\frac{e}{m}V}.$$

The value of e/m is about 1.8×10^7 e.m.u. and the volt is 10^8 e.m.u.   So

$$v = 6 \times 10^7 \sqrt{V} \text{ cm. per second.}$$

If the anode potential is 300 volts, v comes out about 10^9 cm. per second, or 6,000 miles per second.   In a tube whose screen is 20 cm. from the deflecting elements, an electron with this velocity would be at the screen one fifty-millionth of a second after leaving the deflecting field.[1]   So the electron beam is a pointer that can follow the most rapid fluctuations with hardly any delay.   It therefore finds wide use in the observation of surges, high-frequency oscillations, and many other phenomena that are too fast for any mechanical device to follow.   In all this work, electrostatic deflection is used because it is inherently much faster than magnetic deflection.

Cyclic phenomena can be observed by impressing the observed wave on one set of deflecting elements and a timing wave on the other.   If the observed wave is sinusoidal, a sinusoidal timing wave whose frequency is a simple fraction or multiple of the observed wave will give a Lissajous figure.

Practical Cathode-ray Tubes.—In describing a cathode-ray tube, a few problems arise which cause the actual tubes to be different from the simple form of Fig. 35.   One of these problems is the focusing of the electrons in the beam on a small area of the screen, to get a small, intense, luminous spot.   Ordinarily, the stream of electrons will spread out because of electrostatic repulsion.   A second problem is to prevent accumulation of charges on the screen and glass, for that would create a fluctuating field that would ruin the stability of any focusing obtained.   Another problem is to decide on the value of accelerating potential that will effect the best compromise between sensitivity of deflection and brightness of the spot.   For the faster the electrons travel down the tube the more difficult it is to deflect them; but if they are slowed down the spot on the screen is not so bright and not so easy to see or to photograph as when the electrons are moving fast.

Typical Tubes.—In general there are two types of tube, the gaseous and the vacuum.   In the former, molecules of gas positively charged tend to force the electrons together into a com-

[1] JOHNSON, J. B , *Jour. Franklin Inst.*, vol. 212, No. 6, December, 1931.

pact beam. Otherwise they would naturally tend to fly from each other into a wide beam poorly defined at the screen. In other words the gas is utilized to concentrate the electrons in the beam. In the high vacuum tube the electrons are concentrated and made to focus at the proper point on the screen by means of electrodes with potentials under the control of the user.

The voltages used in cathode-ray tubes are of the order of a few hundred to many thousand volts. Modern, high-vacuum tubes operate at voltages of the order of 5–10,000 volts. For example the RCA-903 9-in. tube uses a maximum of 7,000 volts on the high-voltage electrode, 2,000 volts on the focusing electrode, and consumes a maximum average input power to the fluorescent screen of 10 milliwatts per square centimeter. On the other hand, in gaseous tubes the voltages usually run 500 volts maximum or less.

The RCA-903 is arranged for electromagnetic deflection. The curve in Fig. 38 gives an idea of the deflection sensitivity of a typical magnetic system. The intensity of the illumination on the screen can be judged from the fact that at normal voltages the screen has about 0.01 to 0.08 candlepower per square centimeter.

FIG. 36.—Persistence characteristics of fluorescent screen (RCA-903).

Sweep Circuits.—To properly observe many phenomena with a cathode-ray tube it is necessary to sweep the electron beam across the screen at some desired rate with respect to time. Such a scheme gives a plot of the magnitude of the wave motion under study as a function of time.

This is done by deflecting the electron beam of the tube by two fields. One field is varied according to the magnitude
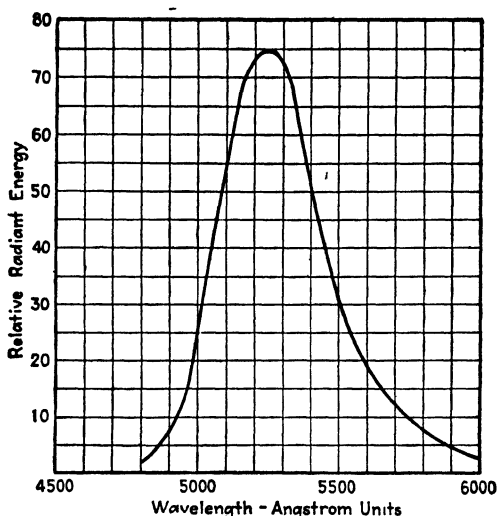
Fig. 37.—Spectral characteristics of typical cathode-ray tube.

of the wave at any instant; the other field, placed at right angles to the first, is controlled by a varying voltage representing time. The deflection representing time must start at some predetermined point on the fluorescent screen of the cathode-ray tube, travel across the screen at a uniform rate, and return to begin a new cycle. Since the return period of the beam is not of special interest, is usually nonuniform, and superimposes a second and interfering wave form on the screen, it should be made as small a proportion of the total sweep cycle as possible. It is an additional convenience to have

Fig. 38.—Deflection sensitivity of an iron-core magnetic system.

Electromagnetic Deflecting Field:
Two coils—10,000 turns each, Iron core—¼ inch square, forming closed external magnetic circuit. Pole-face spacing—1.05 in.

the sweep cycle synchronized with the wave form under observation. These requirements are adequately realized by the

use of a relaxation-oscillator circuit for control of timing voltage. ·

A simple sweep-circuit oscillator is shown in Fig. 40. Condenser *C* is charged by battery *B* through resistance *R*. The
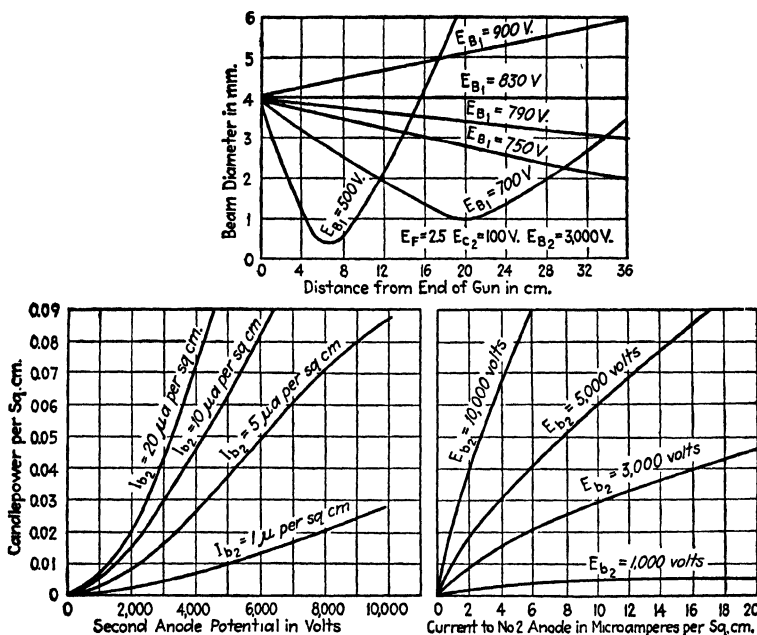
Fig. 39.—Characteristics of typical high-vacuum tubes. Upper curve shows focusing effect of varying voltages.

grid-bias voltage E_c prevents current flow through the grid-controlled rectifier tube until the voltage across the condenser and plate circuit reaches the breakdown value. At this point, the condenser discharges through the tube and loses its potential.
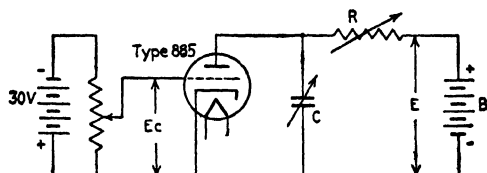
Fig. 40.—Simple sweep circuit using current-limiting resistor.

As soon as the condenser voltage drops below the ionization potential of the tube, the negative grid attracts any positive ions to itself and drives any electrons to the other tube elements, thus de-ionizing the space between cathode and plate.

During the de-ionization period, the condenser discharge current ceases to flow, the grid resumes control, the condenser starts to charge for a new cycle.

Linear Timing Axis.[1]—A simple sweep-circuit oscillator using a resistor to limit the charging rate does not give a linear time axis desirable for observing many cyclic phenomena. In such a timing wave the horizontal deflecting wave periodically moves

E_{cc}=*Battery bleeder circuit, or self-biasing resistor suitably bypassed*
R_1= *700 ohms, or less, depending on requirements*
C_1, C_2, C_3, = *Different shunt condensers*
L = *Synchronizing pick up coil having as low an impedance as practical*
GR = *Connection to ground as well as to anode No 2 of cathode-ray tube*
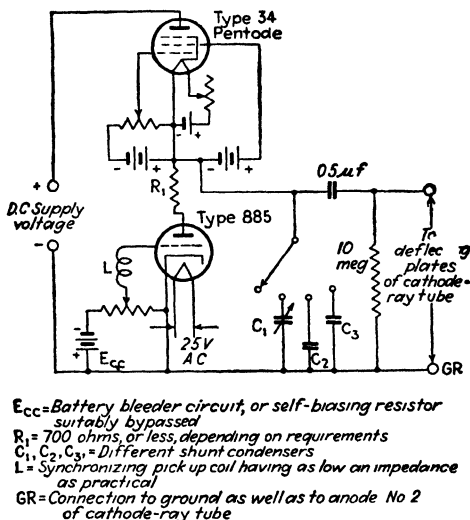
Fig. 41.—Circuit constants for linear sweep circuit using current-limiting pentode
(*RCA Radiotron, Inc.*).

the spot across the screen at uniform speed and then snaps it back to the starting point. The vertical deflection then will cause the spot to trace out a curve against time. If the timing frequency is an integral multiple or submultiple of the observed frequency, the pattern on the screen will be stationary and show directly the form of the observed wave.

To obtain a linear time axis it is necessary to replace the resistor R of Fig. 40 by a device which will limit the current flow to a constant rate. Methods for limiting current flow may employ an emission-saturated diode, a tetrode, or a pentode. The use of tetrode or pentode is preferable since the diode may not have a sufficiently definite saturation current.

[1] A bibliography on the subject will be found in SAMUEL, A. L., *Rev. Sci. Instruments*, vol. 2, pp. 532–540, September, 1931.

Pentode Gas-tube Timing Circuit.—A pentode as compared with a tetrode supplies uniform current over a larger voltage-changing range. Figure 41[1] illustrates the use of a pentode as a current-limiting device. The resistance R_1 connected in series with the plate of the 885 is used to limit the peak current during discharge to a safe value for the tube. Ordinarily, this resistor does not appreciably increase the discharge period.
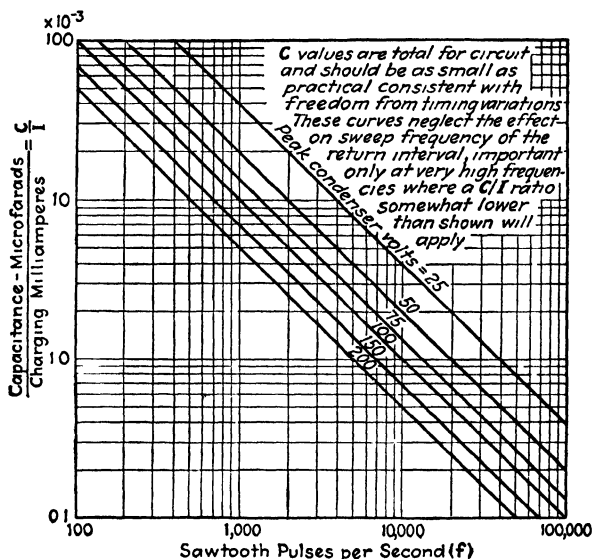
Fig. 42. —Relation between pulse frequency and capacity and current.

The time required to charge C_1, C_2 or C_3 of Fig. 41 to any voltage V is VC/I, where I is a uniform charging rate in amperes. The number of sweeps or sawtooth pulses per second is then I/VC. This expression neglects the time required for discharge, a factor of importance only at very high frequencies. The relationship between sawtooth pulses per second and C/I for several peak condenser voltages (peak sawtooth voltages) is shown graphically in Fig. 42. C represents the total capacity of the circuit and includes tube and wiring capacities. The size of the condenser employed for any operating condition will, therefore, be smaller than the values taken from Fig. 42.

[1] See HALLER, CECIL E , A Linear Timing Axis for Cathode Oscilloscopes, *Rev. Sci. Instruments*, July, 1933. See also bibliography below.

Bibliography

On sweep circuits see the following:

SUNDT, E. V., and G. H. FETT, A Timing Method for Cathode Ray Oscillographs, *Rev. Sci. Instruments*, November, 1934, p. 402.

A Signal-synchronized Sweep Circuit, *Electronics*, May, 1935.

MANN, E. R., A Device for Showing the Direction of Motion of the Oscilloscope Spot, *Rev. Sci. Instruments*, June, 1934, p. 214.

On cathode-ray tubes and applications see:

STINCHFIELD, J. M., *Elec. Eng.*, December, 1934, p. 1609; *Electronics*, May, 1935, p. 153.

SCHRODER, H. J., *Electronics*, June, 1936.

BATCHER, RALPH R., *Instruments*, July, 1935, to January, 1936. An excellent series of articles on this subject.

Electron Relay for Automatic Operation of Cathode-ray Oscillographs, *Brown-Boveri Rev.*, December, 1935; reviewed in *Electronics*, February, 1936, p. 42.

HUGHES, H. K., Thyratron Selector for Double Trace Cathode Ray Oscillograph, *Rev. Sci. Instruments*, February, 1936, p. 89.

The circuit described by Hughes is one whereby two entirely independent wave forms may be observed simultaneously on the screen of the cathode-ray oscillograph. The two waves are sent through separate transformers to suppressor modulate two type-57 vacuum tubes. By a special combination of a grid-controlled rectifier and ordinary neon diode, a square wave is obtained which is applied to the control grids of the 57's, biasing first one and then the other to cut-off. See VON ARDENNE, *Electronics*, October, 1936, on a double-beam tube.

MACGREGOR-MORRIS and HENLEY, "Cathode Ray Oscillography," Chapman & Hall, London, Instruments Publishing Co., Pittsburgh.

The bibliography on cathode-ray tubes is enormous. Batcher's articles are particularly well documented.

Applications of the Cathode-ray Tube.—Low-voltage tubes are widely used for frequency measurements, measuring modulation percentages, determination of the relation between two quantities in the same circuit each varying with time; determining the extent or amplitude of any variable quantity, such as current, voltage, sound or mechanical vibration, etc. The high-voltage tube is applicable to these uses and in addition can be used for recording transient phenomena such as time-voltage characteristic of spark gaps and insulation, transmission-line disturbances, lightning-arrester studies, transients or radio frequencies, mechanical-vibration tests, pressure in guns, gas engines, etc., magneto- or spark-coil discharge studies, oil circuit-breaker and switching problems, determination of wave form of periodic phenomena, characteristics of mercury-vapor lamps and rectifiers, piezo-electric crystal oscillation studies, etc.

Although most uses of the cathode-ray tube and cathode-ray tube oscillograph are of a laboratory nature, there is little doubt that these useful electron tubes will find their way into industrial service either as measuring devices or even as control mechanisms. The two cases described below for using the tube as a production test device are typical. Studies of the effect of putting resistors in the spark-plug leads of gas engines for suppressing radiation have shown automobile manufacturers a great deal about the conditions within the explosion chamber. The use of cathode-ray tubes for measuring vibration, acceleration, the comparative virtues of various types of automobile chassis springs and tires and upholstery has taken place since the first edition of this book was published in 1934. Already the tubes have been used in studies of heart beats and nerve response.
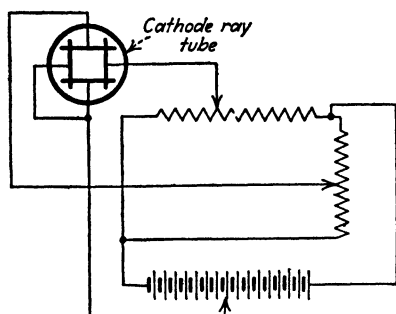
Fig. 43.—Circuit of electronic pencil— the Cathautograph of DuMont.

The Cathautograph.—An interesting application of the general principles described above has been made by Allen B. DuMont.[1] Instead of using a screen with a short decay period, a screen is made which holds the "picture" for periods up to an appreciable fraction of a minute. Thus, a recurrent phenomenon, or transient, can be made to paint on the screen its entire course which will persist long enough to photograph it, or to thoroughly investigate it with the eye. By suitably arranging a stylus which will give the proper voltages to the horizontal and vertical deflection plates, a message in script can be put on the screen. About ten words can be seen on the fluorescent screen before the first one begins to fade. The applications of this idea to interstation communication by either wire or radio are obvious. Transmission of maps, foreign language messages in facsimile, weather reports have been suggested.

Volume-control Inspection.—The testing of variable resistances[2] such as volume controls and tone controls has always

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[1] *Electronics*, January, 1933; *Proc. Radio Club Am.*, vol. 10, No. 3, March, 1933; *Proc. I.R.E.*

[2] PODOLSKY, LEON, *Electronics*, July, 1933.

presented a problem since they are usually tapered in resistance value corresponding to certain degrees of angular rotation. The diagram shown in Fig. 45 is the circuit diagram of a device employing a cathode-ray tube to test the resistance taper of variable resistances. A jig, in which the control to be tested
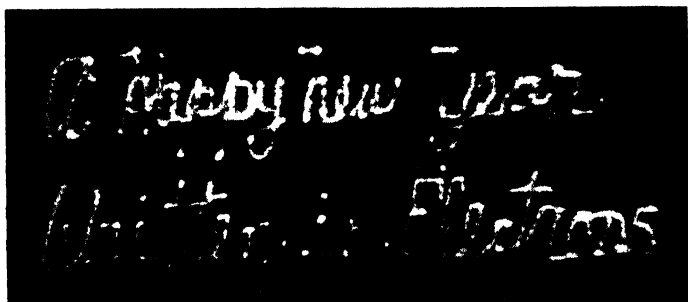
FIG. 44.—Specimen of writing made by Cathautograph.

is placed, is arranged so that a standard variable resistance of the correct taper can be rotated at the same time as the unit to be tested. In the diagram the standard resistance and the control being tested are indicated. As can be seen from the diagram, the cathode-ray tube is one having two sets of deflection plates and the circuit is so arranged that the voltage picked off the control under test is applied across the other set of plates. The electron beam of the tube can thus be made to move in any
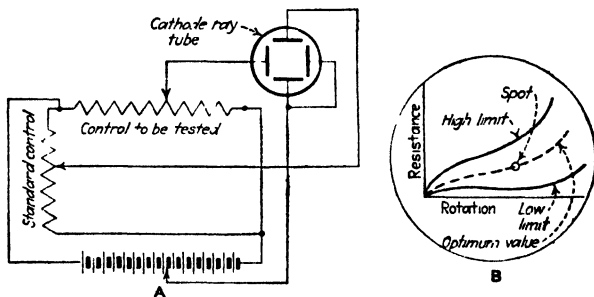
FIG. 45.—Use of cathode-ray tube to match visually response of a circuit element against a normal curve.

desired direction, proportional to the resistance values of the standard control and the control under test. The desired resistance curve can be drawn on the face of the cathode-ray tube, together with the limits of resistance variation, as shown in Fig. 45. The operator in production has only to place controls

to be tested in a test jig associated with the properly calibrated and marked cathode-ray tube and to follow the spot on the tube as the control is rotated. If the spot remains between the limit curves throughout the rotation of the control, the control is satisfactory. If the spot moves outside the limit curves, it is rejected. Thus a continuous check on the resistance taper of any control can be had rather than the usual tolerance check at only two or three points of the rotation.

Use of cathode-ray tubes for testing coils for radio receivers against standard inductances has been made in several plants. In one, in particular, an entire battery of cathode-ray tube outfits is constantly in use by unskilled operators who match (by adjustment of the individual coils) a characteristic of a coil against a standard curve.

Cathode Rays External to the Tube.—In the usual cathode-ray tube the electrons (the cathode rays) are allowed to impinge on a screen of willemite or other substance which glows when the electron hits it. Some success has been had with permitting the electrons to escape from the tube through a thin sheet of metal and to impinge on substances or objects not in the vacuum of the tube itself. Such a tube is called a Lenard tube or a Lenard ray tube.

Although it is too early to judge what industrial value these rays will have, it is interesting to note the results of an experimental study in the research laboratory of the General Electric Company. The gases of the air with which they come in contact are ionized. The ionized nitrogen becomes visible and the extent to which the electrons go out into the higher pressure space outside the tube may be estimated roughly by noting the extent of the luminous glow around the end of the tube.

Many substances fluoresce brightly when bombarded by cathode rays; other substances phosphoresce for some time after the bombardment ceases. Calcite crystals, for example, remain highly luminescent some hours after being bombarded. Willemite is brilliantly green but does not phosphoresce. The temperature of the object under the path of the rays has some effect upon the color of the fluorescent radiation. Calcite, for example, is bright yellow at 150°C., orange at room temperature, and a dark pink at liquid-air temperature. The luminescence and phosphorescence of minerals depend to a large degree on the

presence of impurities. This has been found to be the case in sapphires, for instance, so that by raying a sapphire one can differentiate between a natural and a synthetic specimen and tell the origin of a natural specimen.

Some substances undergo a more or less permanent change in color as a result of raying by high-speed electrons. Glass is a good example. Manganese glass becomes purple; lead glass becomes brown after radiation. It has been suggested that the cathode-ray tube become a means for coloring glass. Although
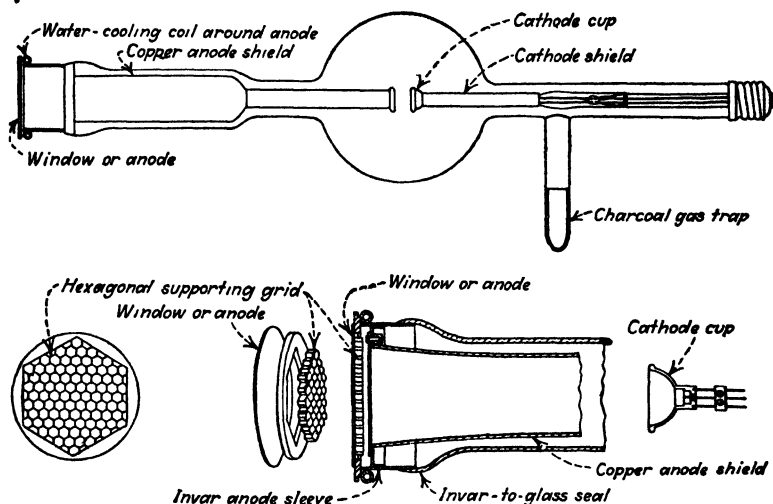
Fig. 46.—High-voltage tube from which cathode rays (beams of electrons) are permitted to escape.

some of the hue fades, sufficient remains to produce a marked color effect.

Various chemical salts are changed in color by a similar process. X-rays are found to be given off by the air in front of the window or by any substance which the rays hit. This permits a method of x-ray analysis of unknown substances that has given very satisfactory results on alloys.

Many interested effects have been found to be produced on organic chemicals by the cathode rays. Gaseous formaldehyde, for instance, is polymerized and the resultant solid paraformaldehyde is broken up. This is typical of many other effects, for they all seem to consist of formations of molecular clusters followed by disintegration into simple gases.

Oils like linseed and china-wood oils undergo a change in molecular weight, refractive index, and drying rate when rayed. An interesting effect on inorganic substances is the reaction between hydrogen and oxygen which takes place under the influence of the electrons; peroxide, water, and ozone are all produced.

In biological experiments, a leaf of a rubber plant was found to be covered with white latex after exposure to the rays, showing that the cell walls had probably been punctured. In barley seeds, death or mutations can be produced. Carcinoma and tuberculosis of the skin, and chronic eczema have been successfully treated with the rays. Many kinds of bacteria can be killed by exposure to them. The thickness of thin delicate tissues can be measured by exposing a photographic plate to rays coming through the tissue. Also, the thickness of thin films of any material having a known density can be measured in the same way with the advantage that the precision does not decrease with decreasing thickness of the film.

When, for example, cholesterol, yeast, and other alimentary products are exposed to the rays, vitamin D is produced. The product is not so potent as that which can be obtained from use of ultra-violet rays because the cathode rays seem to break down the vitamin after having built it up. Similarly, the effect of the rays on the skin of a rat is to build up vitamin D, but they will not cure rickets because they kill the rat first. It might be thought that the cathode rays produce the vitamin indirectly by causing emission of ultra-violet, but it has been shown experimentally that this is not the case.

Indicator Tube.—The application of cathode rays to indicating various changes in a mechanical or electrical set-up has just begun. Anything that can be translated into a varying electrical voltage may be made visible by permitting a beam of electrons to impinge upon a target, or screen, which becomes fluorescent. Late in 1935, a tube especially made for this kind of work was brought on the market. It is known as the 6E5 and consists of a triode amplifier and a target on which the electrons produce a fluorescent pattern of varying dimension depending upon the voltage impressed upon the triode grid. While this tube has been applied largely as a tuning indicator for radio receivers, it has also come into some use as an indicator for other variables.

The tube can be made into a vacuum-tube voltmeter in which the final indication is not a current or voltmeter but is the pattern

of this "magic-eye" tube. Any adjustment now made by watching the needle of an indicating instrument, as the synchronism of two circuits, may be adjusted visually by the use of this tube,
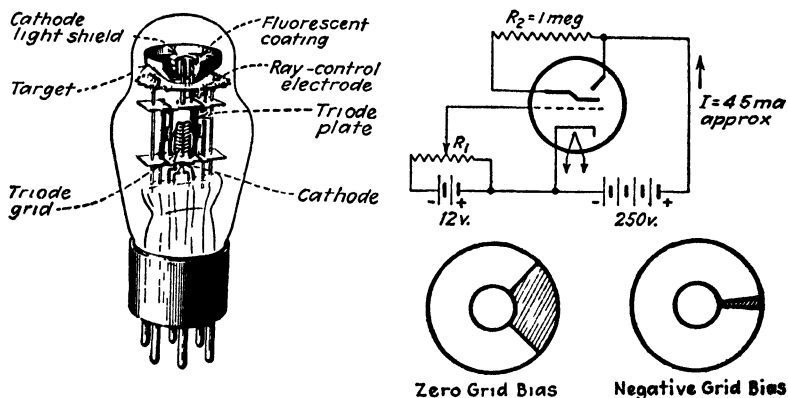
FIG. 47.—6E5 cathode-ray indicator-tube, circuit and patterns.

subject, of course, to the sensitivity of the amplifier-cathode-ray tube in it and the accuracy with which the pattern may be inspected and reproduced.

R₁= 2 megs, 0 5 watt
R₂= 100,000 ohms, 1 watt
R₃= 1 meg, 0 5 watt
R₄= 10,000 ohms, 10 watt
R₅= 1,000-ohm, wire-wound linear potentiometer
R₆= 500 ohms, 2 watt
R₇= 10,000 ohm, 10-watt wire-wound linear potentiometer

C₁=4μf,400v paper (low-leakage)   C₄=0.1μf, 300v paper
C₂C₃C₅= 0 01μf mica   C₆= 8μf,350v electrolytic
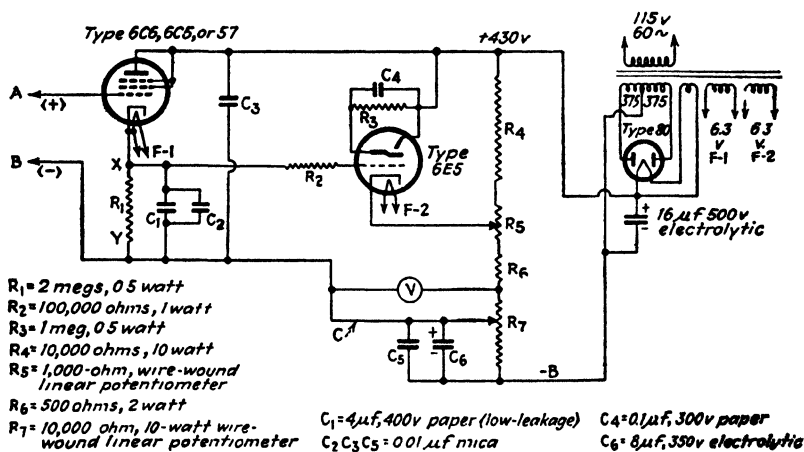
FIG. 48.—Use of indicator tube as a vacuum-tube voltmeter.

For example, the circuit shown in Fig. 48 can be used to measure voltages of the order of 0.5 to 10 volts direct current to an accuracy of plus or minus 0.1 volt.[1]

[1] WALLER, L. C., and P. A. RICHARDS, *Radio Retailing*, December, 1935.

Electron Diffraction.—Industrial use has been made of the fact that electrons have a dual nature, showing sometimes the characteristics of particles and at others the characteristics of waves. Thus a beam of electrons of uniform energy may be regarded as analogous to a train of waves; just as x-rays may be used to investigate crystal structure by diffraction, so can electrons accelerated by high voltages be used, in some cases with considerable advantage over the older art. Phillips[1] states that protons and positrons as well as electrons can be utilized in this manner as a useful research tool for measuring corrosion, for calibrating electrometers up to nearly 400 kv., or for calibrating pressure gages to 4×10^{-11}, studying molecular structure, and investigating thin films, oils, photographic films, etc. He gives a comprehensive bibliography in this paper.

Chemical Analysis.—X-ray analysis of the chemical properties of a substance has proved to be of tremendous importance both as a qualitative measure and as indicating quantitatively the relative constitution of materials. Qualitatively the use of x-rays indicates absolutely the presence or absence of elements. It is particularly useful in the elements of higher atomic weight which are least easily analyzed by other methods.

But there are difficulties; it has been almost necessary to put the material to be tested within the evacuated envelope. The cathode-ray tube, however, has simplified the process by permitting the production of x-rays outside the evacuated tube. A cathode focuses a beam of electrons on an aluminum window a portion of which is thin enough for the electrons to pass through and enter the open atmosphere. Here they are allowed to impinge upon the substance to be analyzed where they produce their characteristic x-ray spectrum. This may be analyzed by the x-ray spectroscope or electrically by means of a low-grid current tube of the type of the FP-54.

X-rays Tubes.—The technique of using x-rays for chemical and mechanical properties is well known and is well covered in books devoted to this special subject. The practice is widely different from the use of other types of electron tube and will not be described here.

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[1] PHILLIPS, C. J., *Electronics*, September, 1935, p. 24.

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